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VACUUM, ELECTRON AND ION TECHNOLOGIES

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Cathodic arc plasma deposition: From fractal spots to energetic condensation

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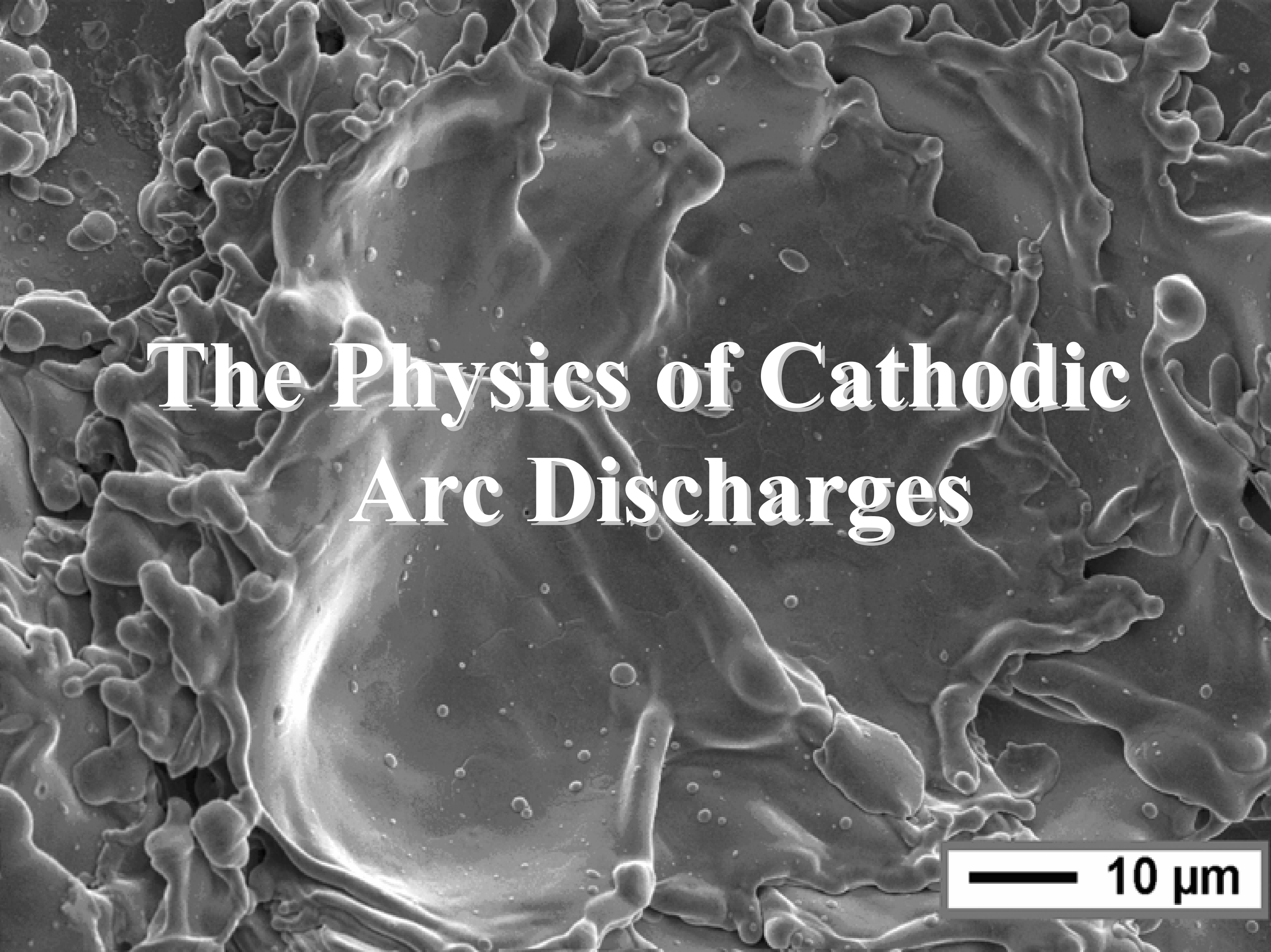
The Physics of Cathodic Arc Discharges

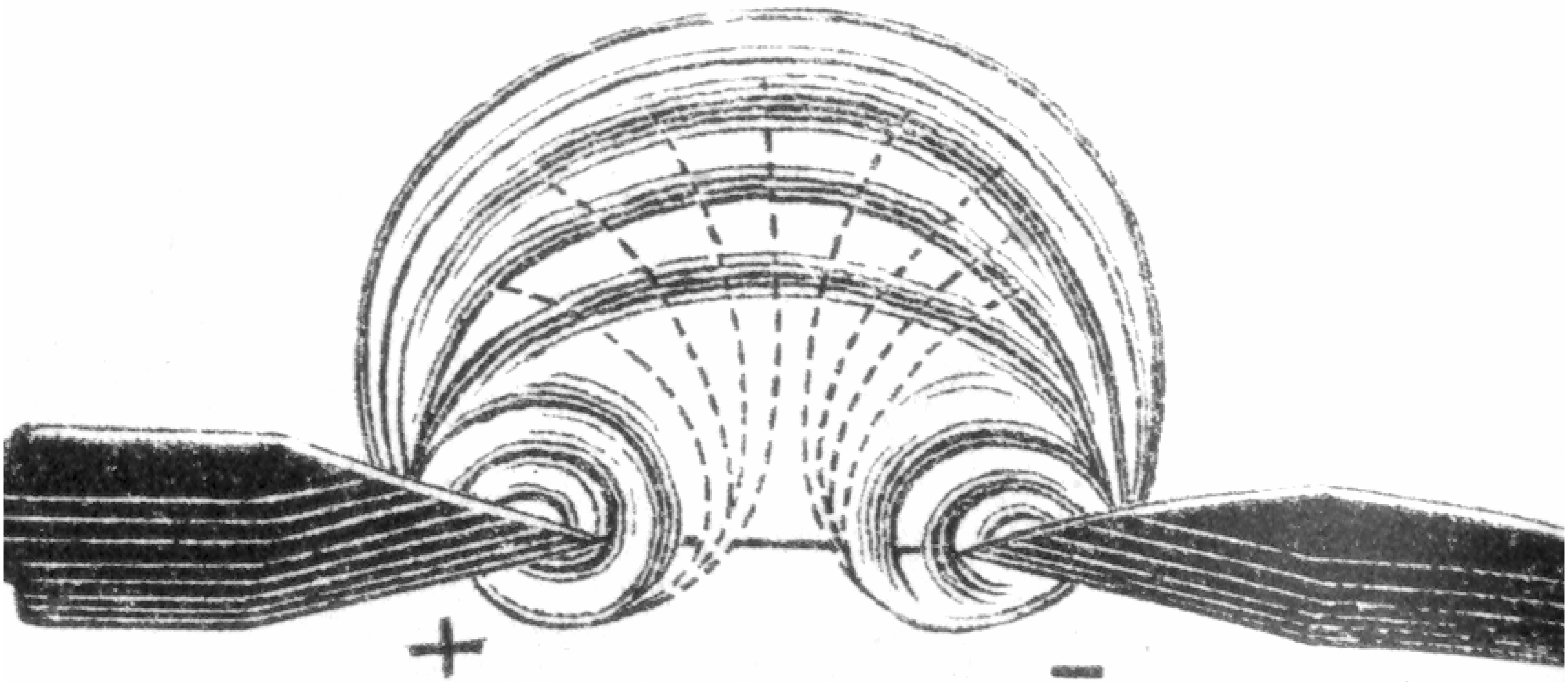


Introduction:
Definitions, Measurements
&
Phenomenology

What is a cathodic (vacuum) arc?

- Arc discharge:
  - Electrical discharge through a plasma, characterized by
    - Relatively high current (typically > 5 A)
    - Relatively low voltage (typically < 50 V)
    - collective electron emission mechanism at the cathode
- "Vacuum" arc discharge:
  - Arc discharge whose plasma is produced at electrodes
- *Cathodic* (vacuum) arc discharge:
  - Vacuum arc discharge whose plasma is produced at cathode spots
- *Anodic* (vacuum) arc discharge:
  - Vacuum arc discharge whose plasma is produced from evaporating anode material

Arc Discharge



Wiedemann, 1885

Arc Discharge

Electron Emission Mechanisms

Physics problem:

- Electron transfer over the cathode's potential barrier

Nature's solution:

- "*collective*" electron emission mechanisms:
  - Thermionic emission
  - Field emission
  - Thermo-field emission
  - Explosive emission (this includes cathode plasma)

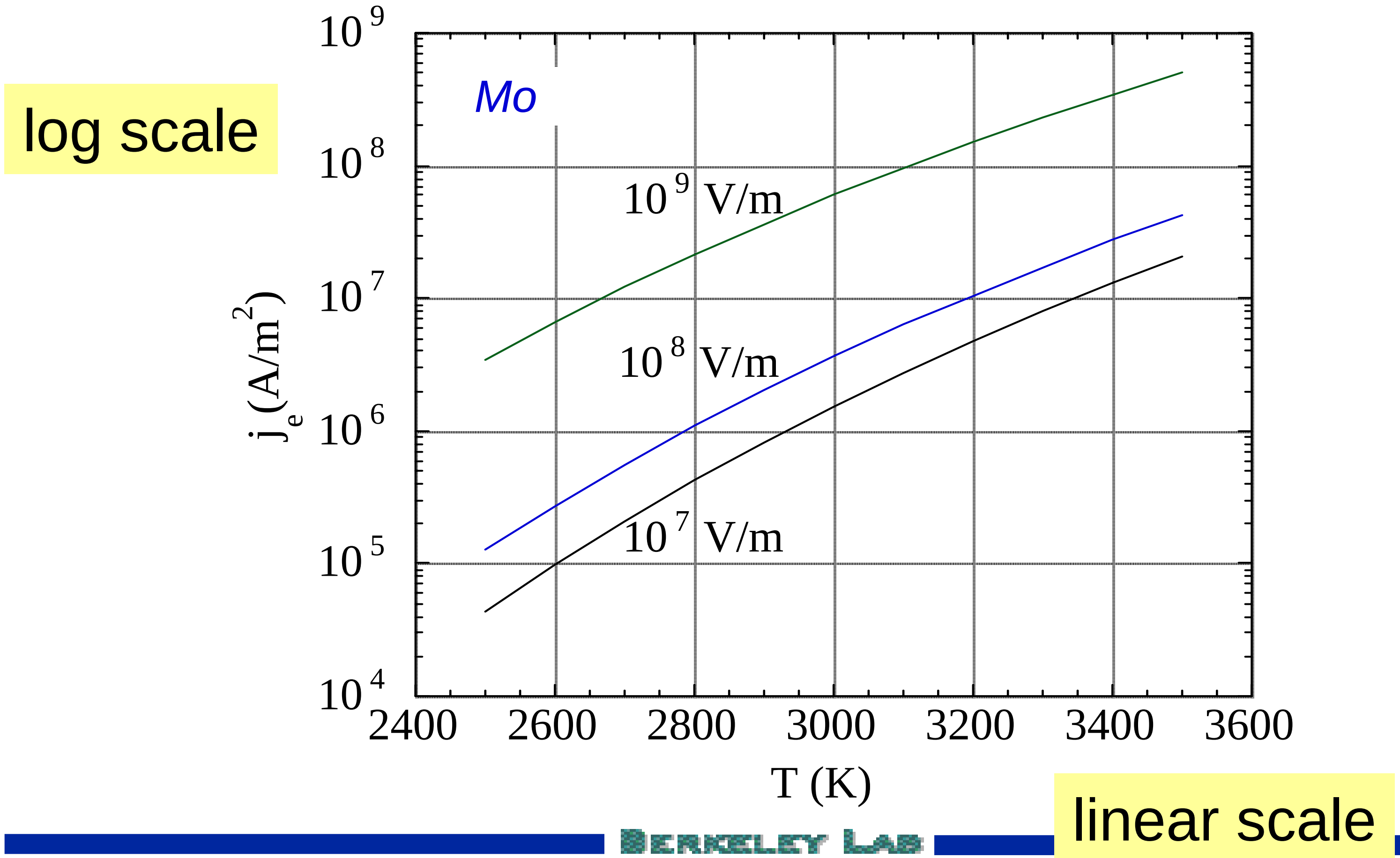
arc discharge

- As opposed to "*individual*" e-emission mechanisms:
  - Secondary electron emission by primary particle impact:
    - Ion
    - Electron
    - Excited / energetic atom
    - Photon

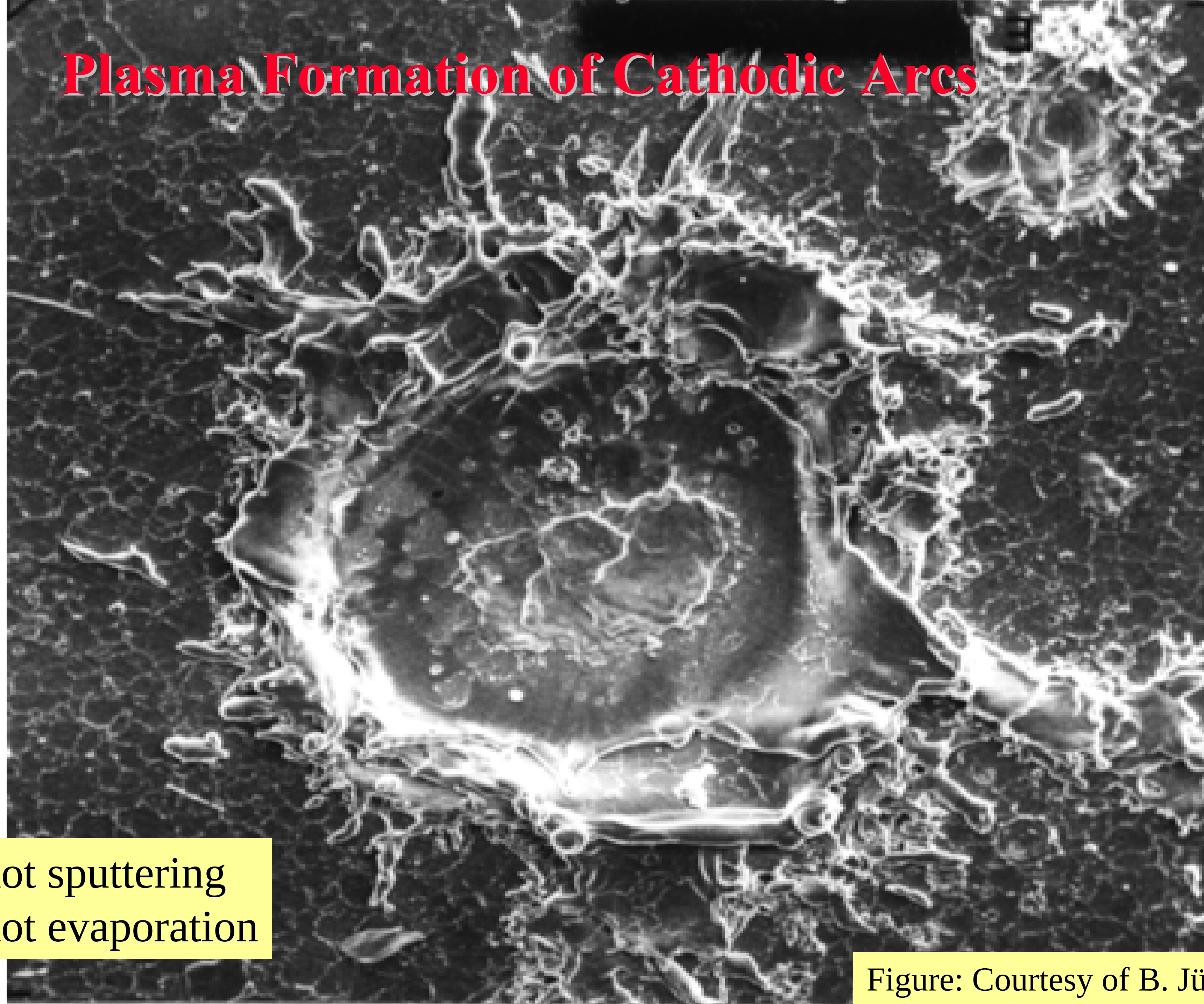
glow discharge

Thermofield Electron Emission

- Current density of thermofield emission is necessarily associated with great power density → plasma formation can become explosive in nanosecond time scale



Plasma Formation of Cathodic Arcs



- not sputtering
- not evaporation

Figure: Courtesy of B. Jüttner

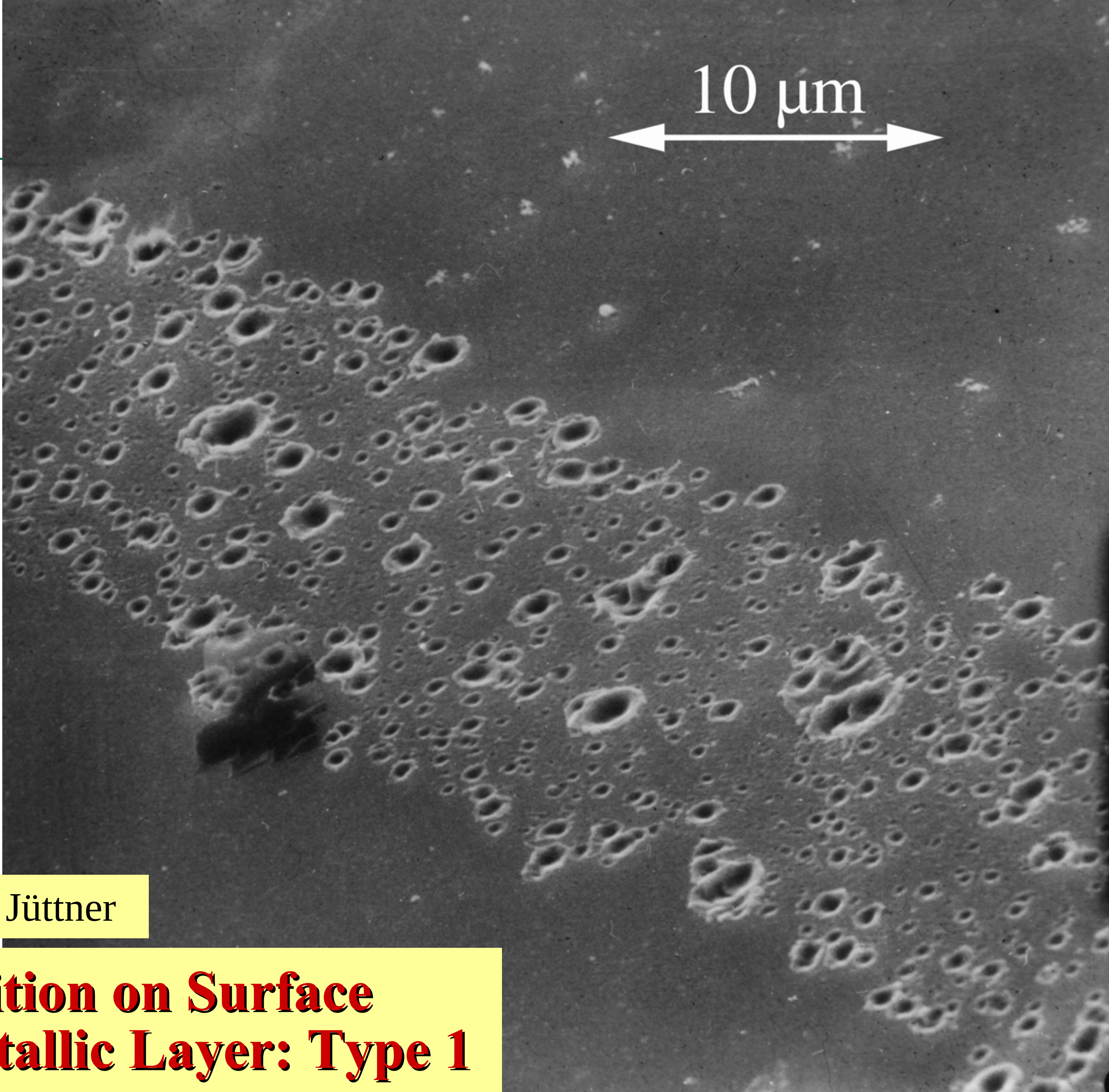


photo courtesy of B. Jüttner

Spot Ignition on Surface with Non-metallic Layer: Type 1

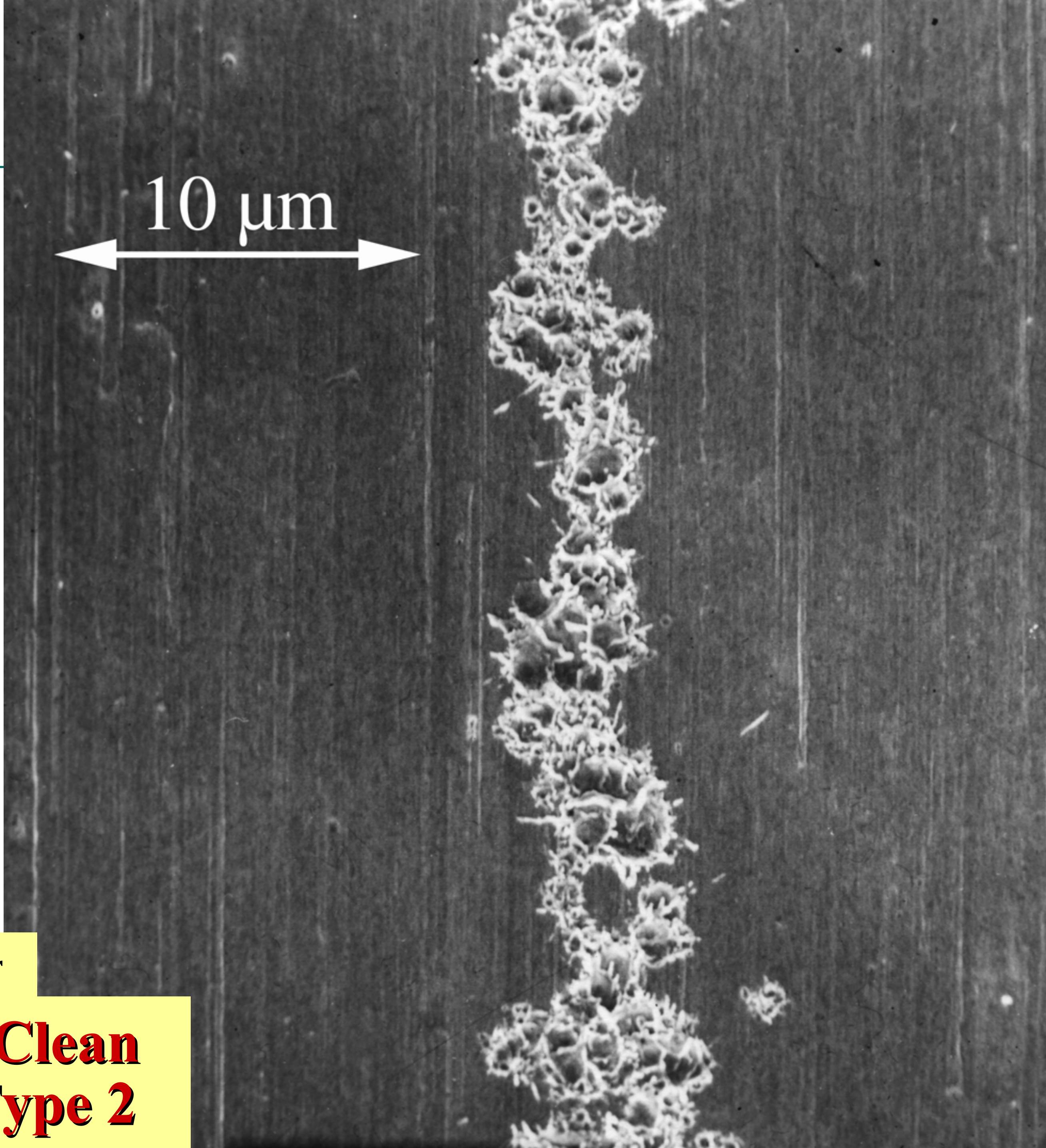
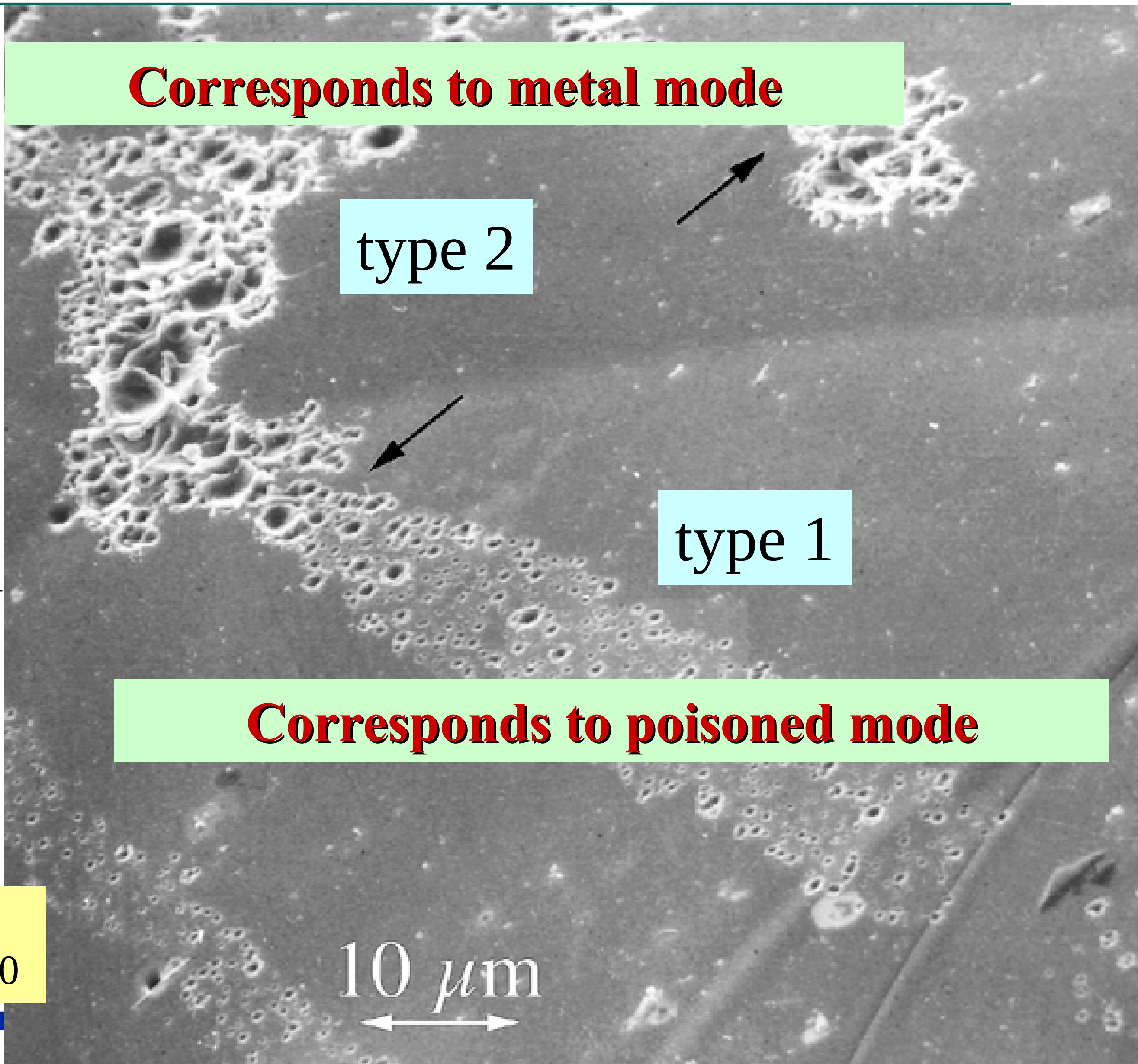


photo courtesy of B. Jüttner

Spot Ignition on Clean Metal Surface: Type 2

The Experimental Basis: Cathode Erosion and Plasma Formation

- arc spots / spot fragments leave crater traces
- type or mode depends on surface condition

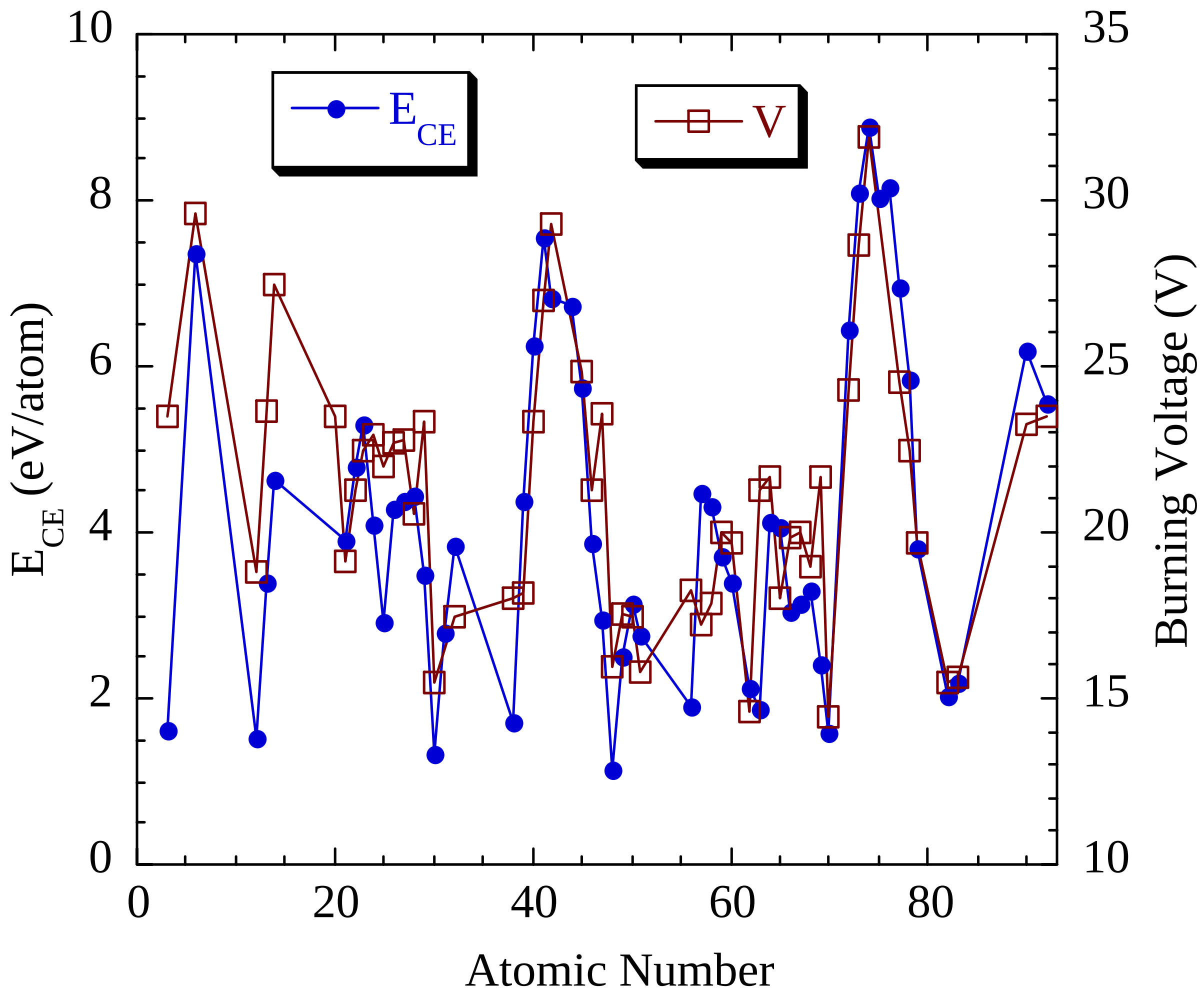


from A. E. Guile, B. Jüttner, ZIE Preprint 80-2, Berlin, 1980

Cohesive Energy Rule

Energy balance consideration:

There is a direct correlation between cohesive energy of the cathode solid and burning voltage of cathodic arc



cohesive energy = energy needed to free an atom from the solid

A. Anders *et al*, J. Appl. Phys. **89** (2001) 7764

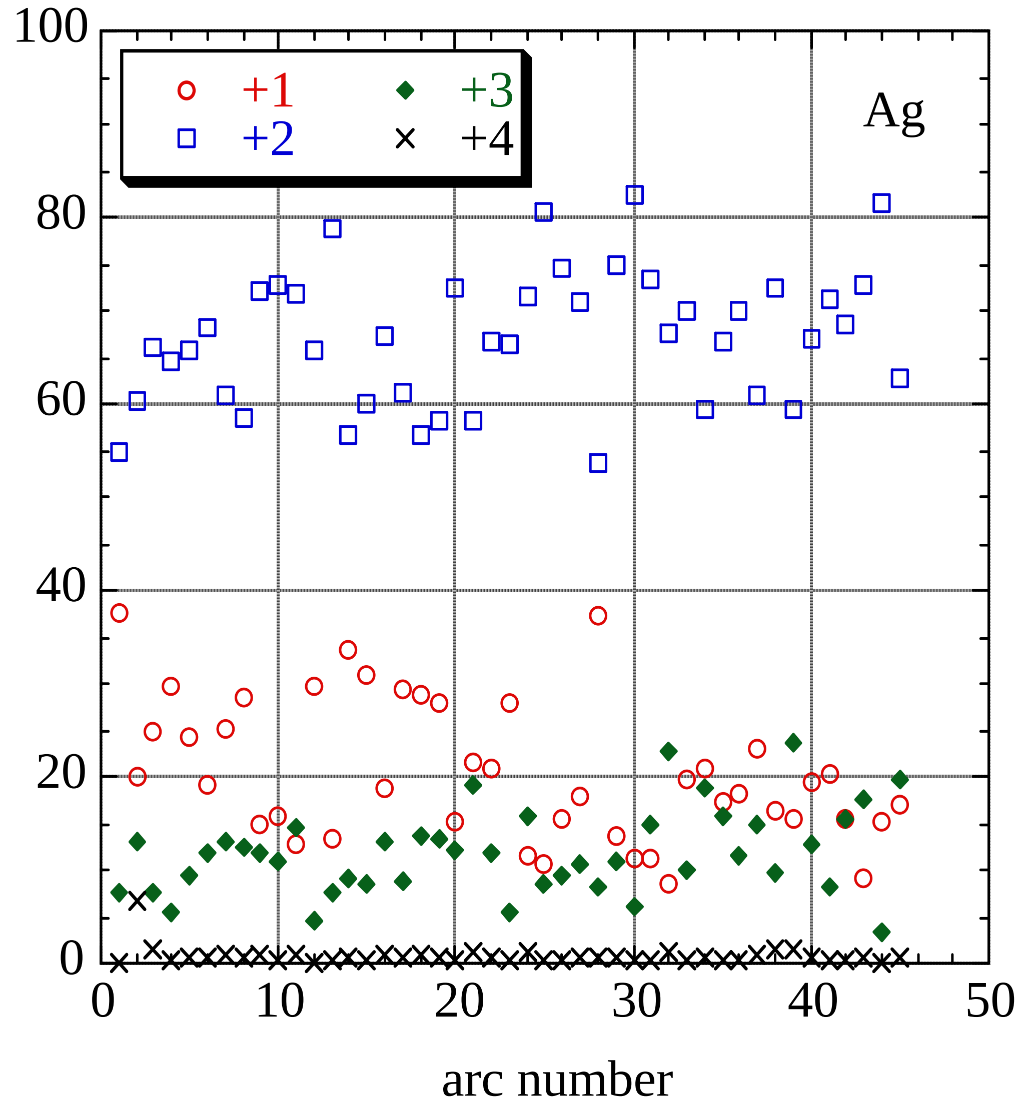
Properties of Cathodic Arc Plasmas

- Plasma expands from near solid state density (10^{27} m^{-3}) in the cathode spot to very rarified plasma far from spot (e.g. down to 10^{14} m^{-3});
- for "large" distances from spot: plasma is in non-equilibrium
- *Jüttner's formula*: in absence of magnetic field and for r > 100 μm $\boxed{n \approx \gamma I_{arc} / r^2}$
- For copper cathode: $\gamma \approx 10^{13}\ \mathrm{A^{-1}m^{-1}}$

- electron temperature near spot 2-4 eV
- Average ion velocity $\boxed{v_i \approx 0.8 - 2.2 \times 10^4\ \mathrm{m/s}}$
- Electron current > arc current (this is not a typo!)

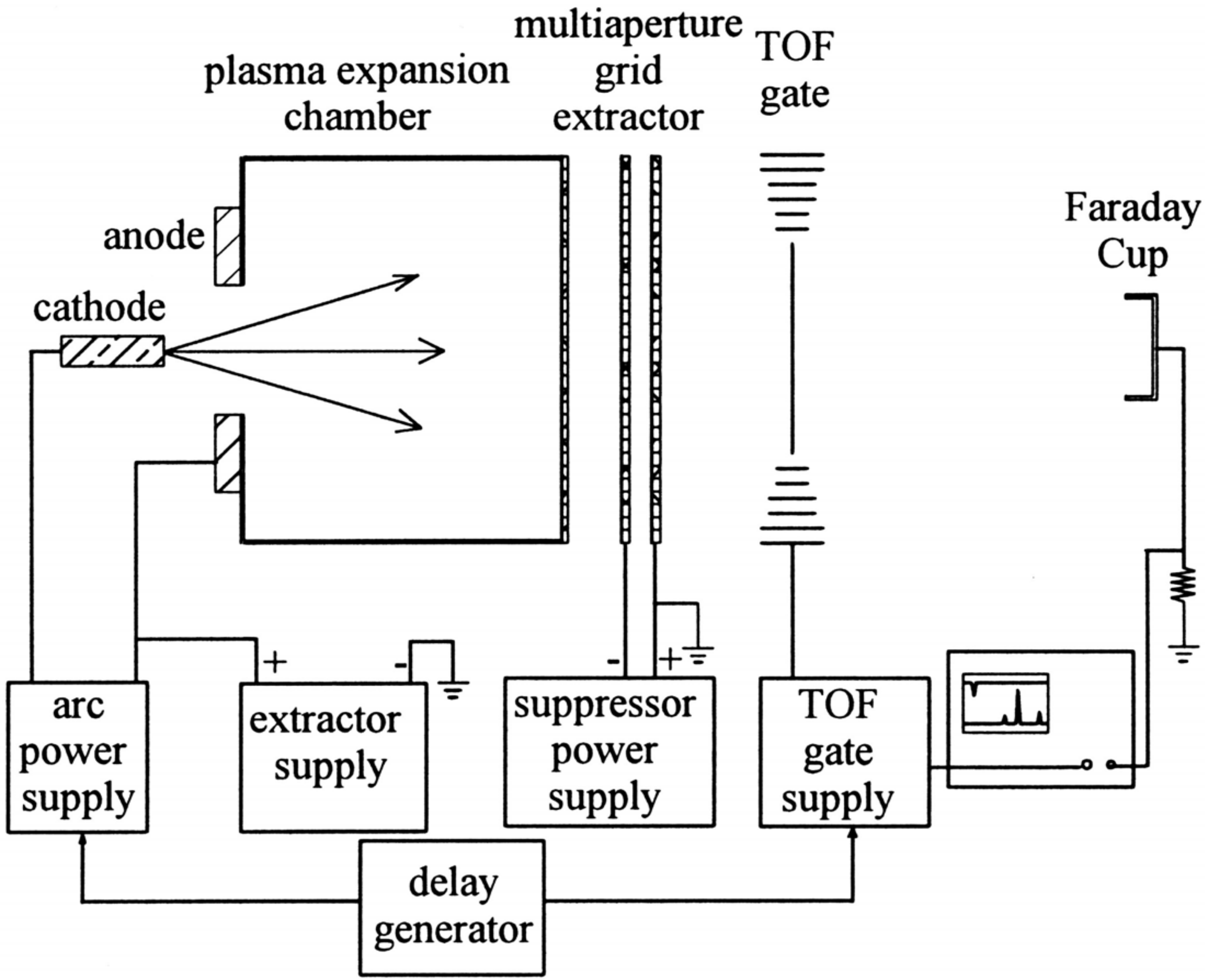
"Noise" or Fluctuations

- Noise due to the explosive nature of plasma production
- Noise is present in practically all parameters (voltage, density, temperature…)
- Noise is of little or no concern for plasma deposition (averaging effect)
- Example: CSD sampling of pulsed silver arc



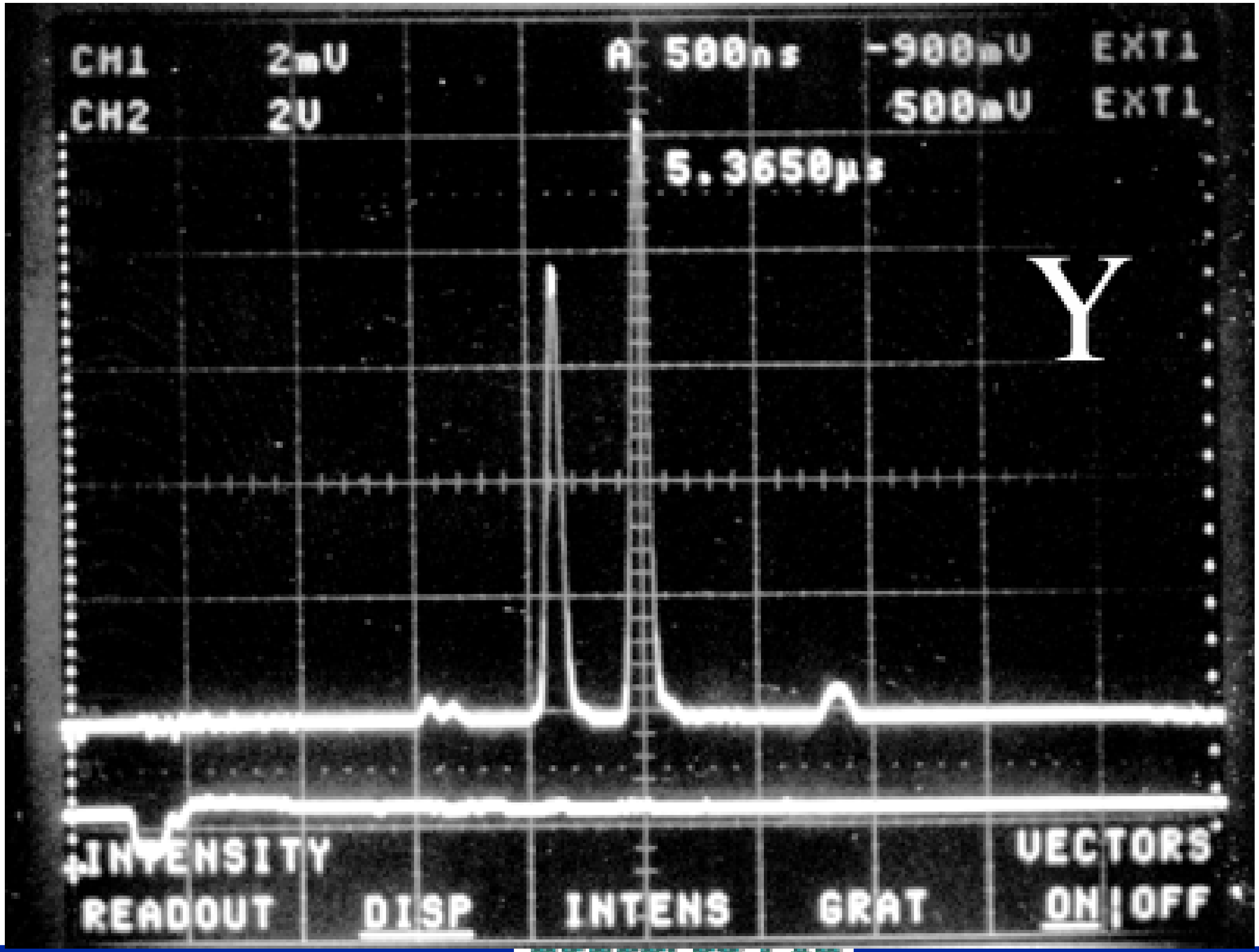
A. Anders, *IEEE Trans. Plasma Sci.* **27** (1999) 1060

Ion Charge-State Spectrometry



Example of TOF Raw Data

- Yttrium plasma, with ion charge states 1+, 2+, and 3+



Ion Charge State Distributions

- Ion charge state distributions (CSDs) of over 50 elements and alloys have been measured:
  - Mean ion charge state typically > 1; CSD is noisy

    Brown, Rev. Sci. Instrum. **65** (1994) 3091

  - CSD is enhanced at beginning of each arc discharge and reaches steady-state after about 100-200 μs
  - CSD can be enhanced by
    - Magnetic field
    - High current (self field)
    - Current spikes

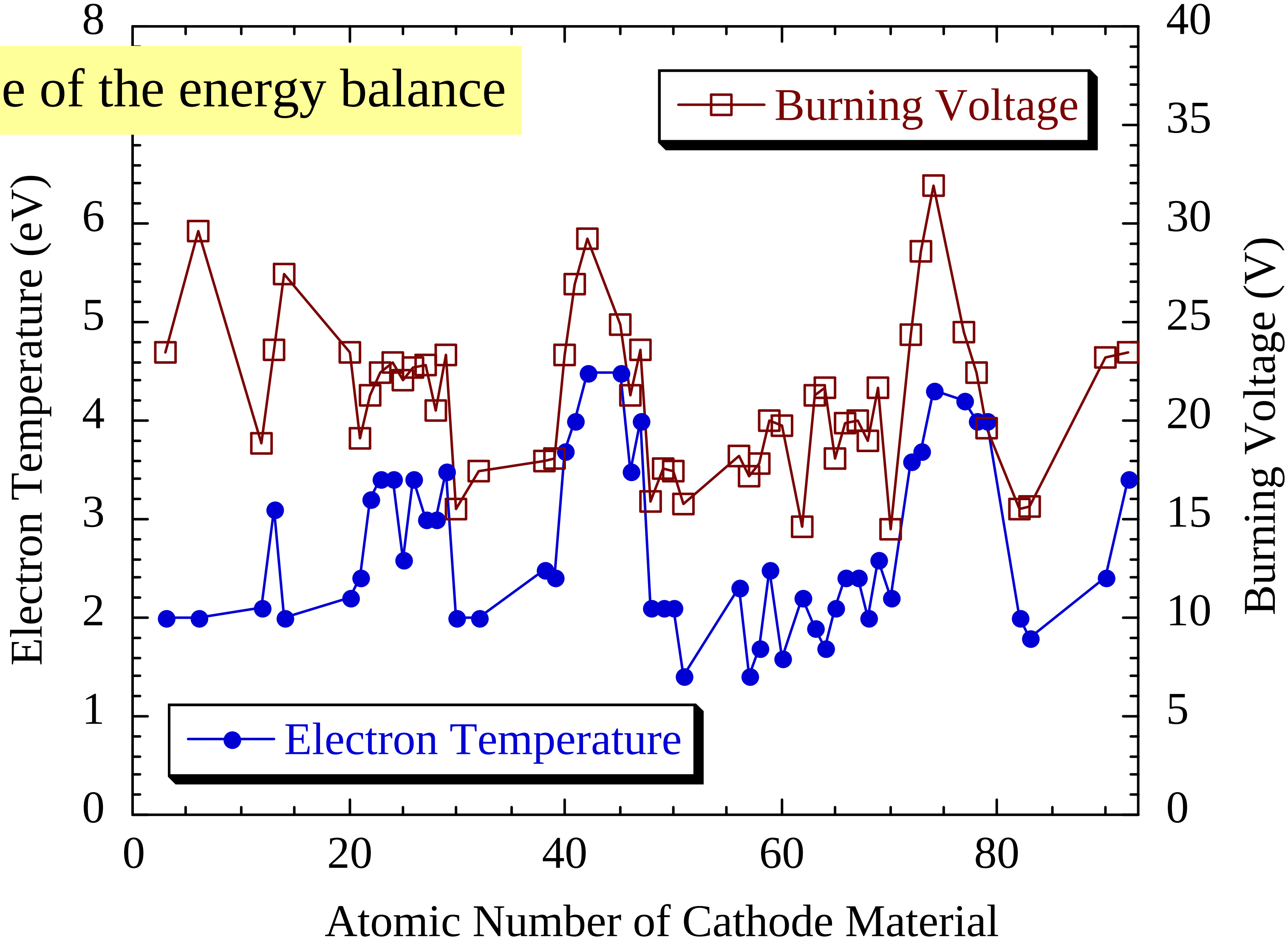
    Oks et al. IEEE Trans. Plasma Sci. **24** (1996) 1174

  - CSD can be reduced by background gas
  - Model of Local Saha Equilibrium includes charge state “freezing”

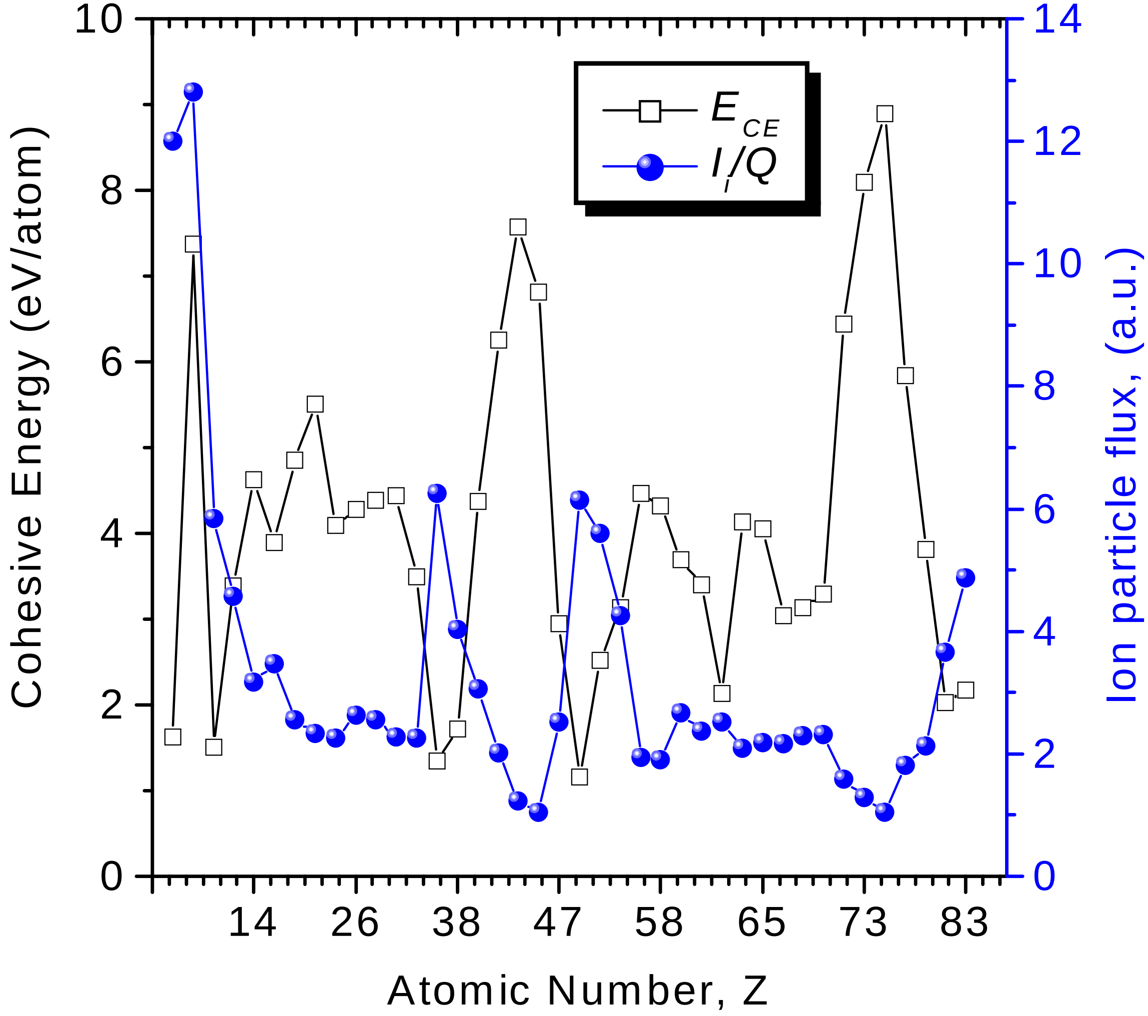
    A. Anders, Phys. Rev. E **55** (1997) 969

Secondary Relations Follow From Cohesive Energy Rule

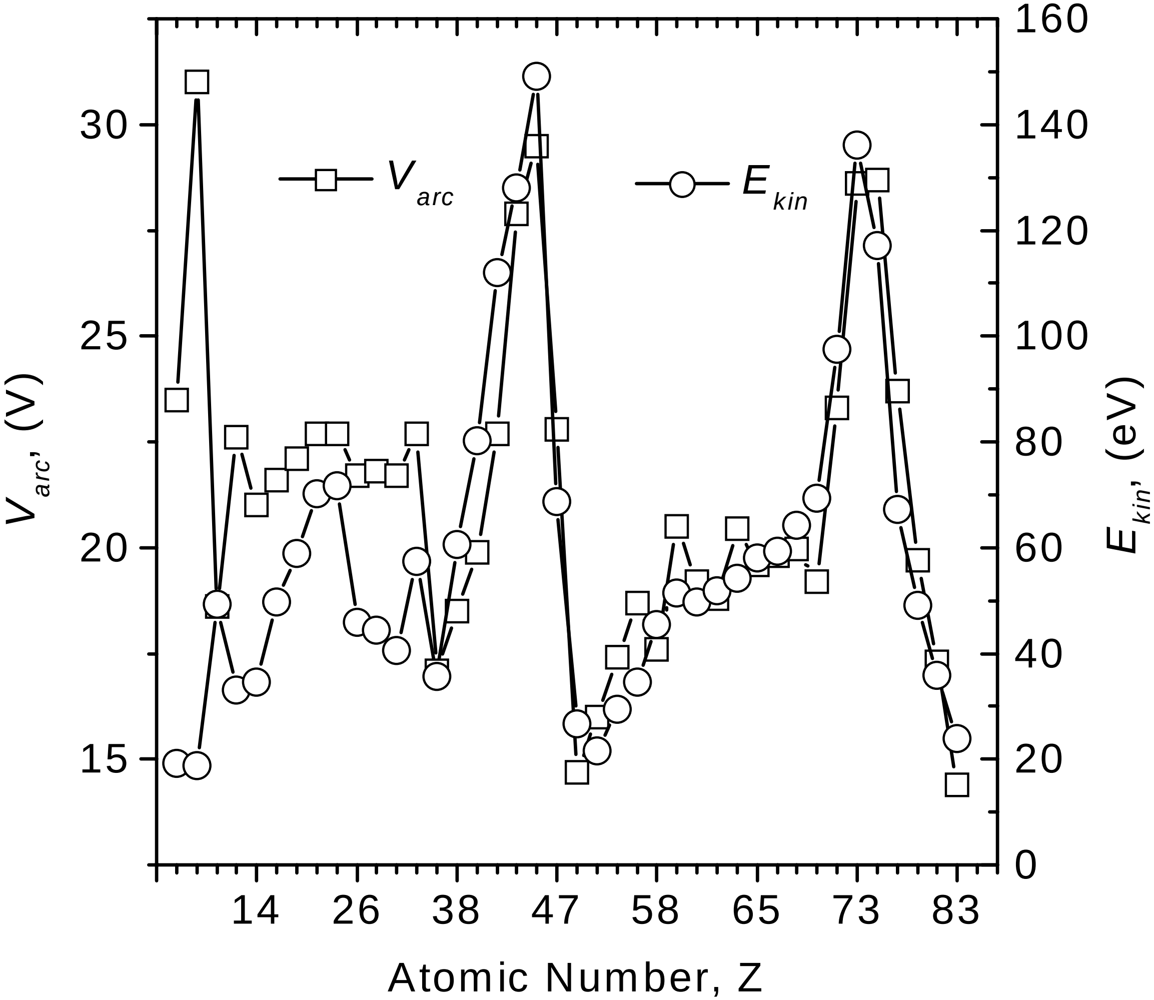
A consequence of the energy balance



Erosion Rate and Cohesive Energy

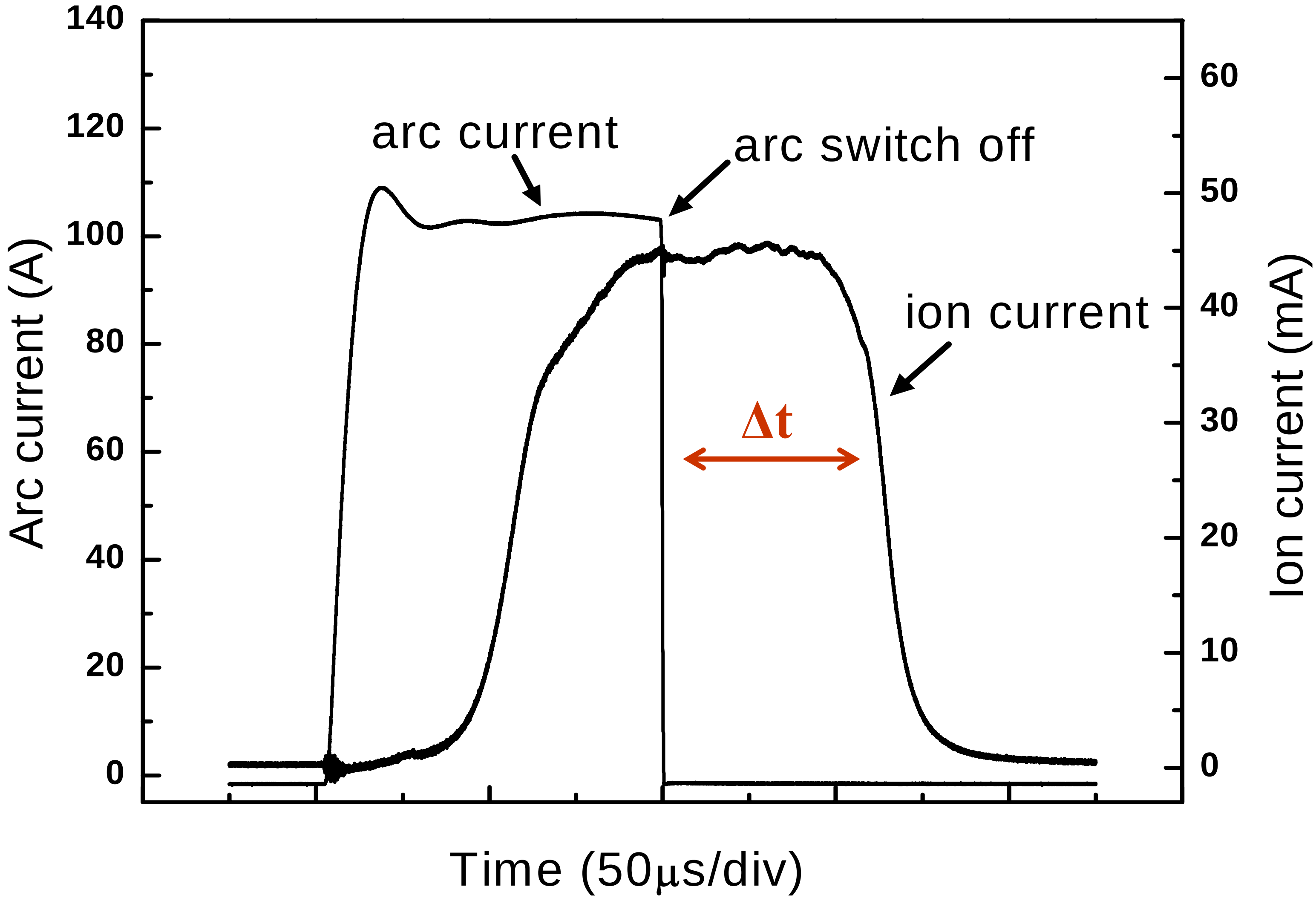


Cohesive Energy Rule Applied to Kinetic Ion Energy



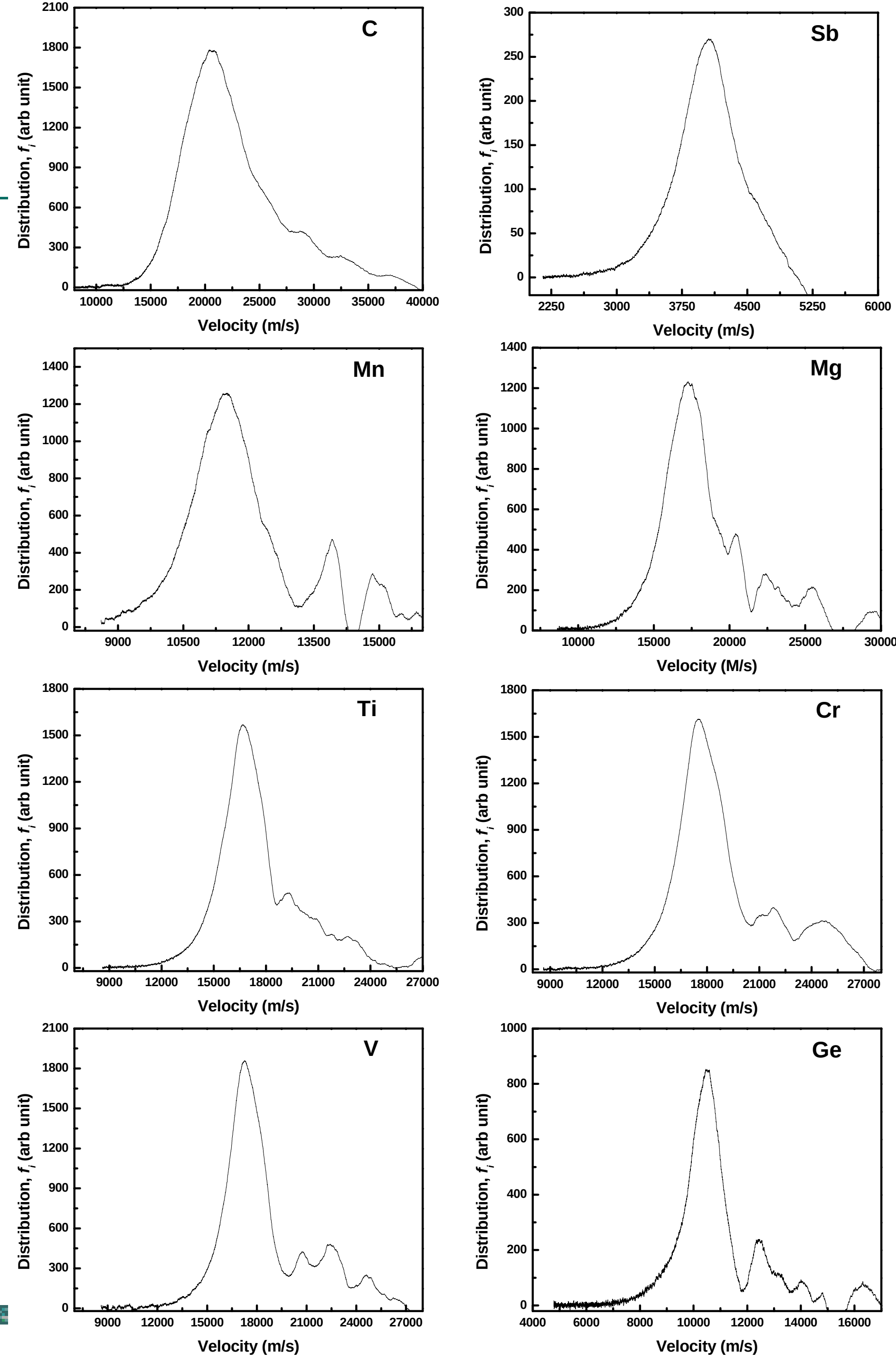
Anders and Yushkov, *J. Appl. Phys.* **91** (2002) 4824-4832

Time-of-Flight Measurement Setup with Current-Zero



TOF Results

- most distributions show ***one*** large peak
- indication that all charge states have about the same velocity i.e. kinetic energy is independent of charge state
- high energy peaks are uncertain and may be related to plasma instabilities



Byon and Anders,
J. Appl. Phys. **93** (2003) 1899-1906

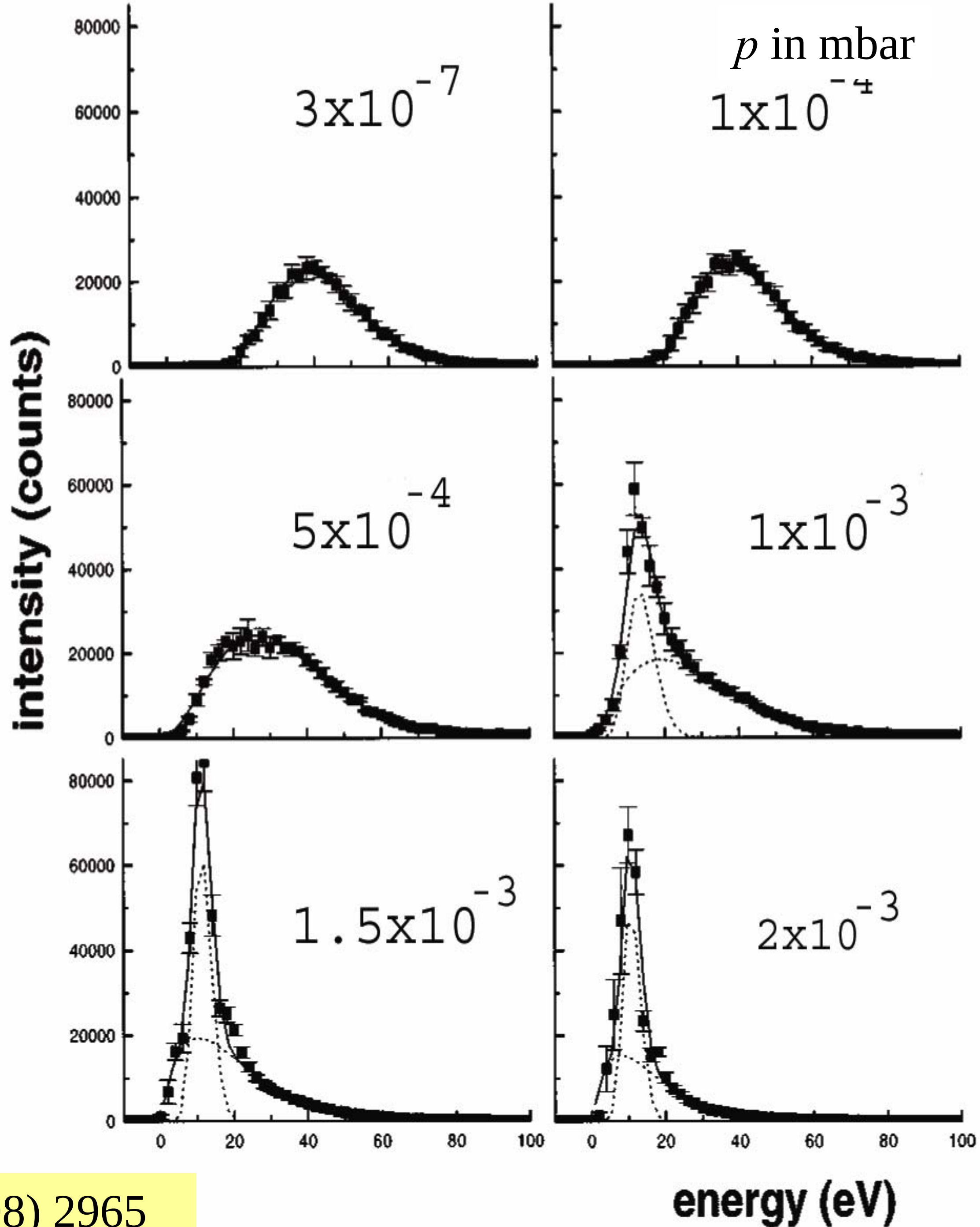
Kinetic Ion Energy With Background Gas

- Presence of gas causes changes in
  - ***plasma production***
  - ***plasma transport***

- changing surface condition of cathode, similar to "poisoning" of sputter target, issue of spot type
- Collisions with gas will shift ion energy distribution function to lower energy
- low-energy peak will appear, representing species that have lost energy in collision

Effect of Gas on Kinetic Energy of Metal Ions

- Example: Ti plasma in nitrogen
- method: mass selective energy analyzer

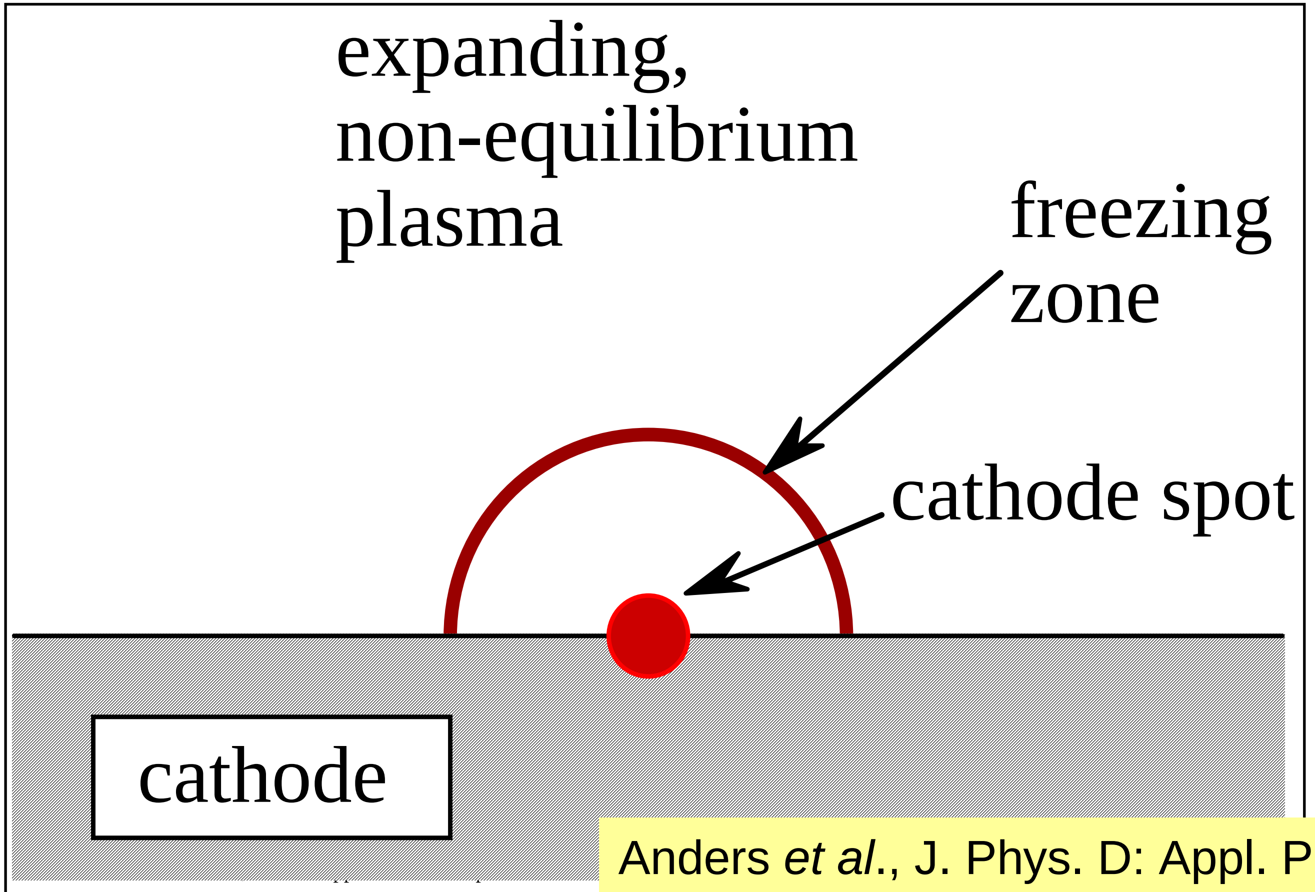


Bilek et al., *J. Appl. Phys*. **83** (1998) 2965

Theory & Models

Model of "Instantaneous Freezing"

- Charge state spectrum reflects plasma condition at equilibrium ⇒ non-equilibrium transition zone, the "freezing zone" near cathode spot



Anders *et al*., J. Phys. D: Appl. Phys. **21** (1988) 213-215

Arc Spot Ignition

Local thermal run-away process leads to micro-explosion and formation of extremely dense plasma:

High electric field, enhanced by

1. protrusion (e.g. roughness, previous arcing)
2. charged dielectrics (e.g. dust particles, flakes)

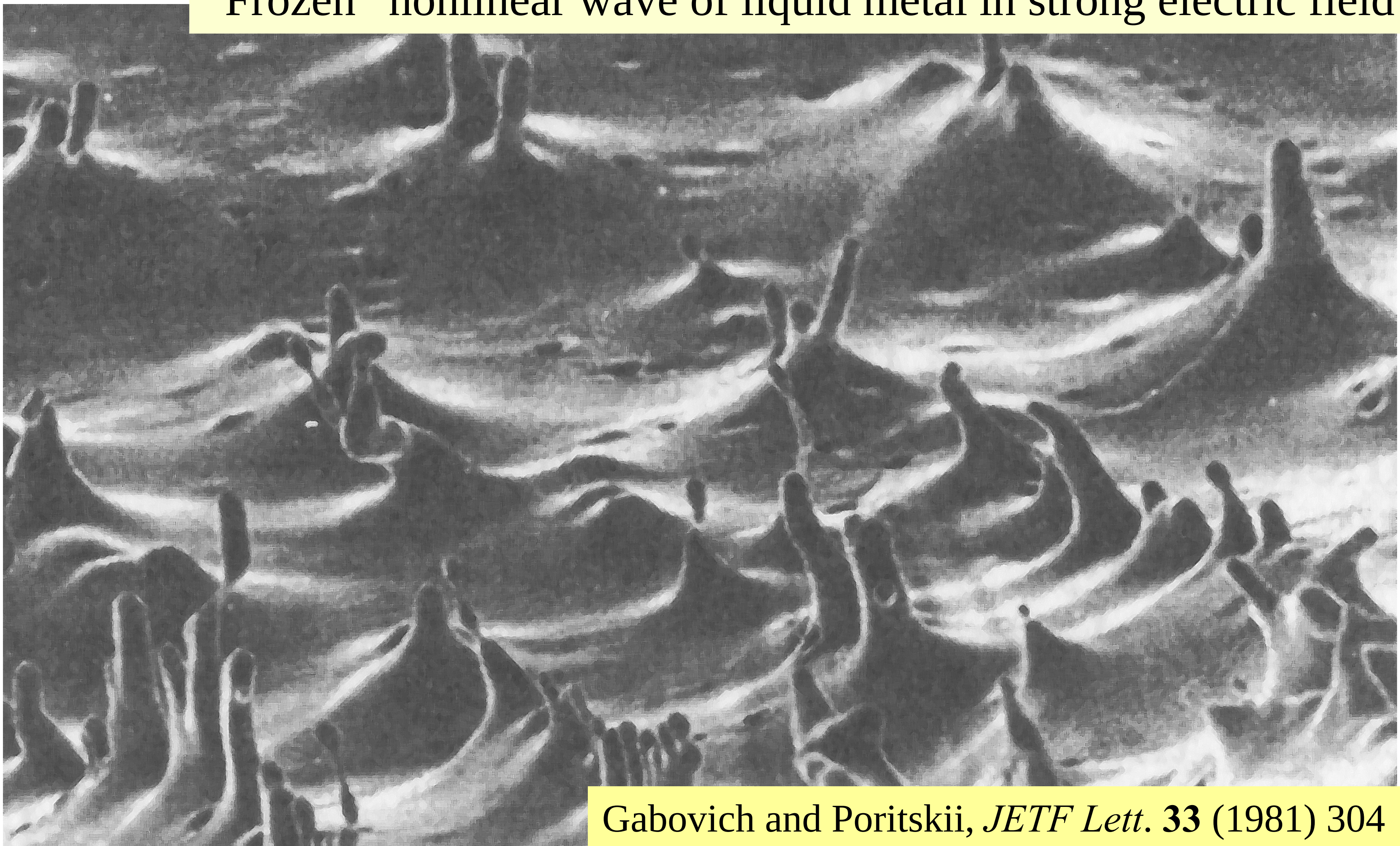
1. higher field leads to locally greater e-emission
2. Joule heat enhances temperature of emission site
3. higher temperature amplifies e-emission non-linearly

feedback!

Runaway!

Explosive Emission and Arc Spot Ignition

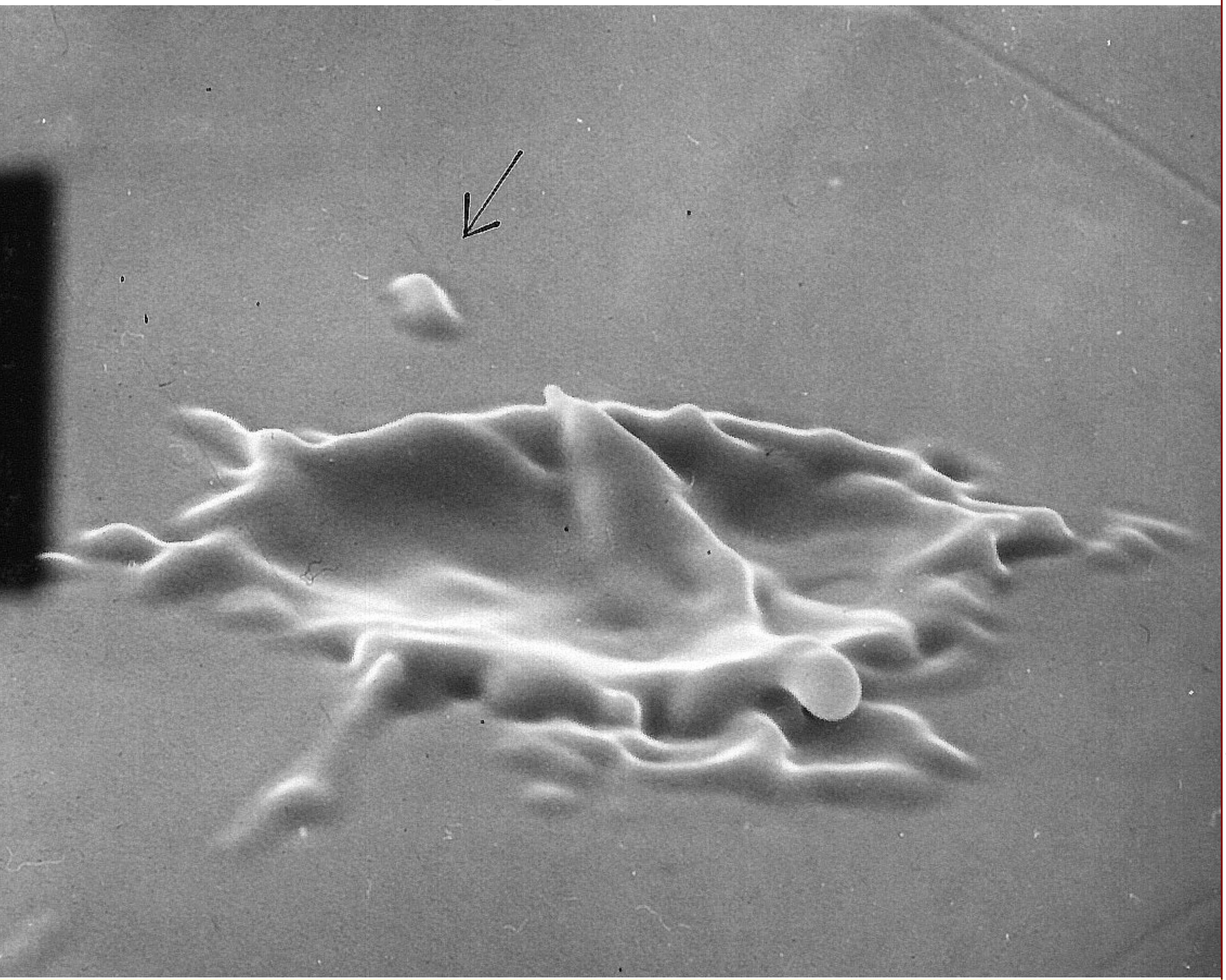
"Frozen" nonlinear wave of liquid metal in strong electric field



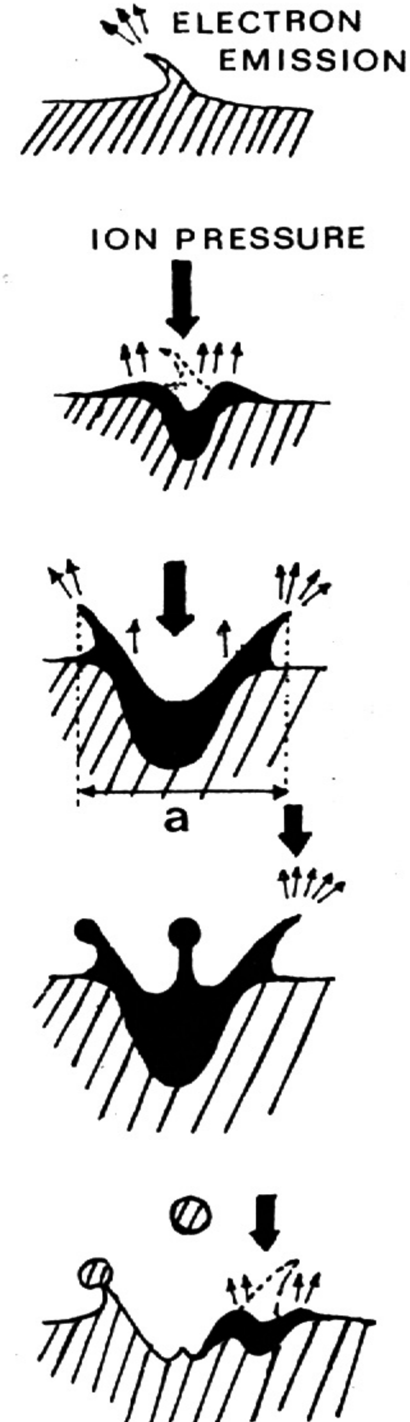
Gabovich and Poritskii, *JETF Lett*. **33** (1981) 304

Macroparticle Formation: Response of a Liquid to Impulse Pressure

Self-Generation of Ignition Conditions

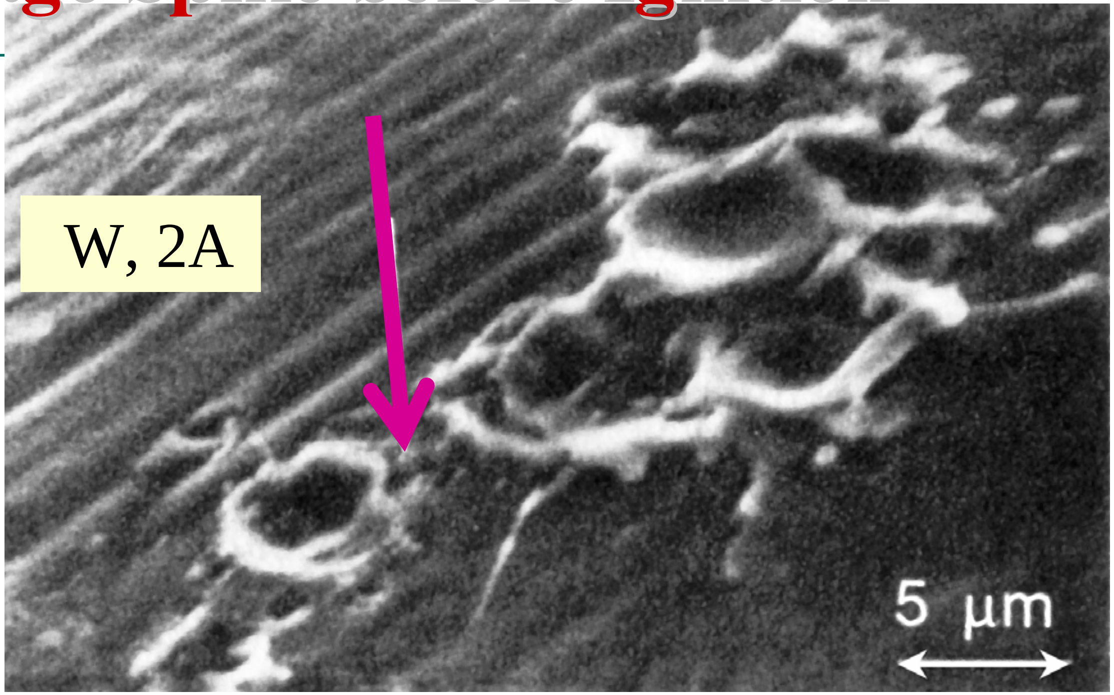


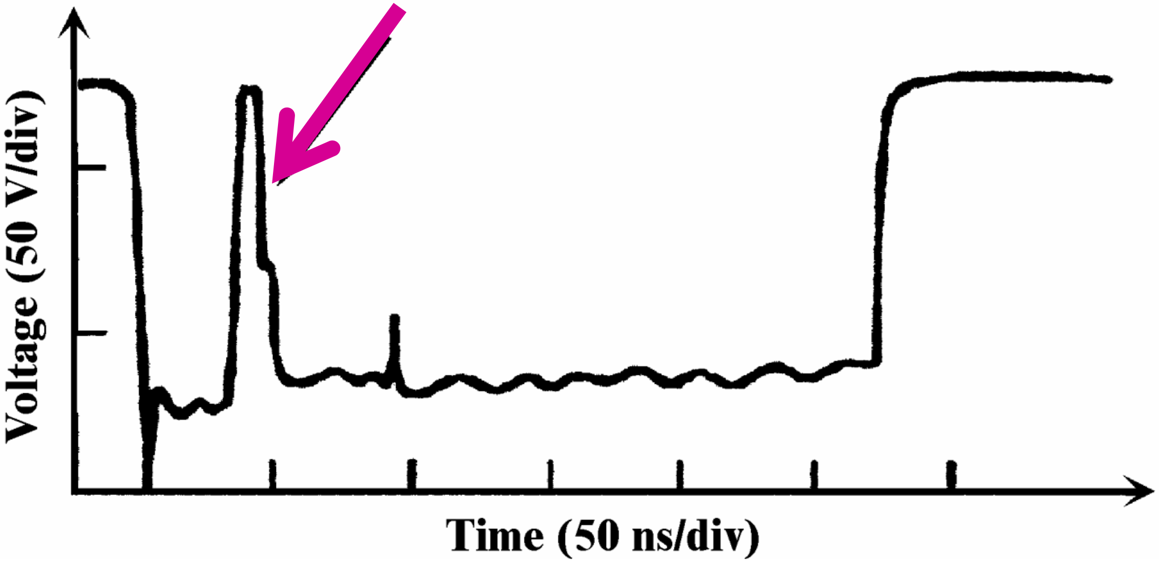
0 ns discharge on Mo. Photo courtesy of B. Jüttner



Voltage Spike before Ignition

Extinction of emission center causes voltage to rise until new center is ignited





Puchkarev and Murzakayev, *J. Phys. D* **23** (1990) 26

Ignition and Types of Spot Motion

- ***Spot motion***: Displacement of active spot by ignition of new spot and extinction of active spot
- for homogenous (uniform) surfaces: ignition probability follows laws of "diffusion-limited aggregation" resulting in "***random walk***"
- for non-uniform surfaces: ignition probability is higher at locations where local electric field is enhanced, especially by dielectric layers, charges, inclusions: ignition probabilities follows laws of "***self-avoiding walk***," i.e. does not ignite where ignition has happened before (conditioning effect!)
- if symmetry is broken by magnetic field: ignition probability is higher at locations where local electric field is enhanced via thinner sheath (higher density under plasma jets): "***steered walk***"

Effects of Layers and Magnetic Field on Spot Ignition

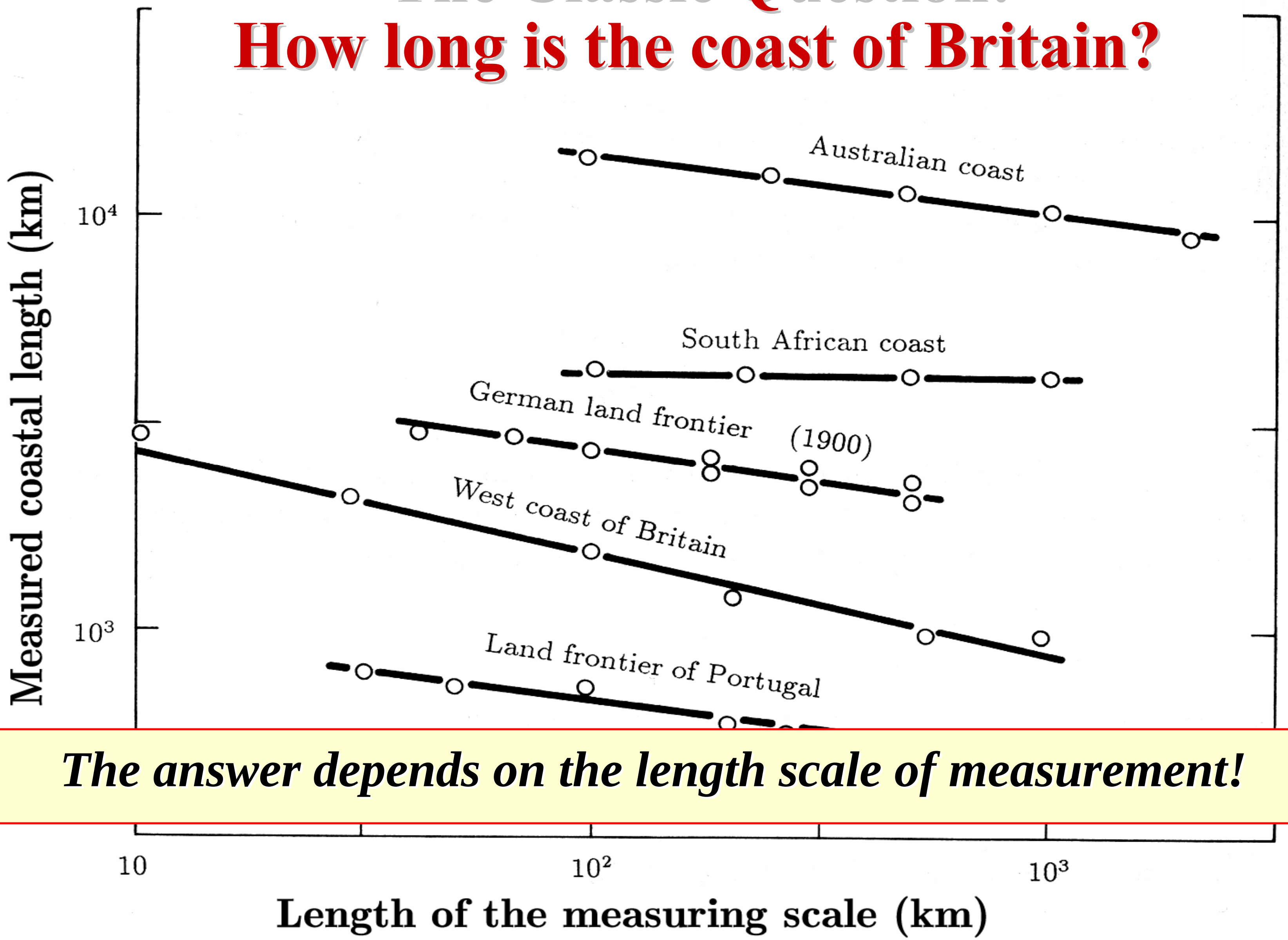
- Both surface layers and magnetic field change probability distribution for spot ignition

↓

- these effects can be described in a single, generalized model: the ***fractal model*** .

Fractals

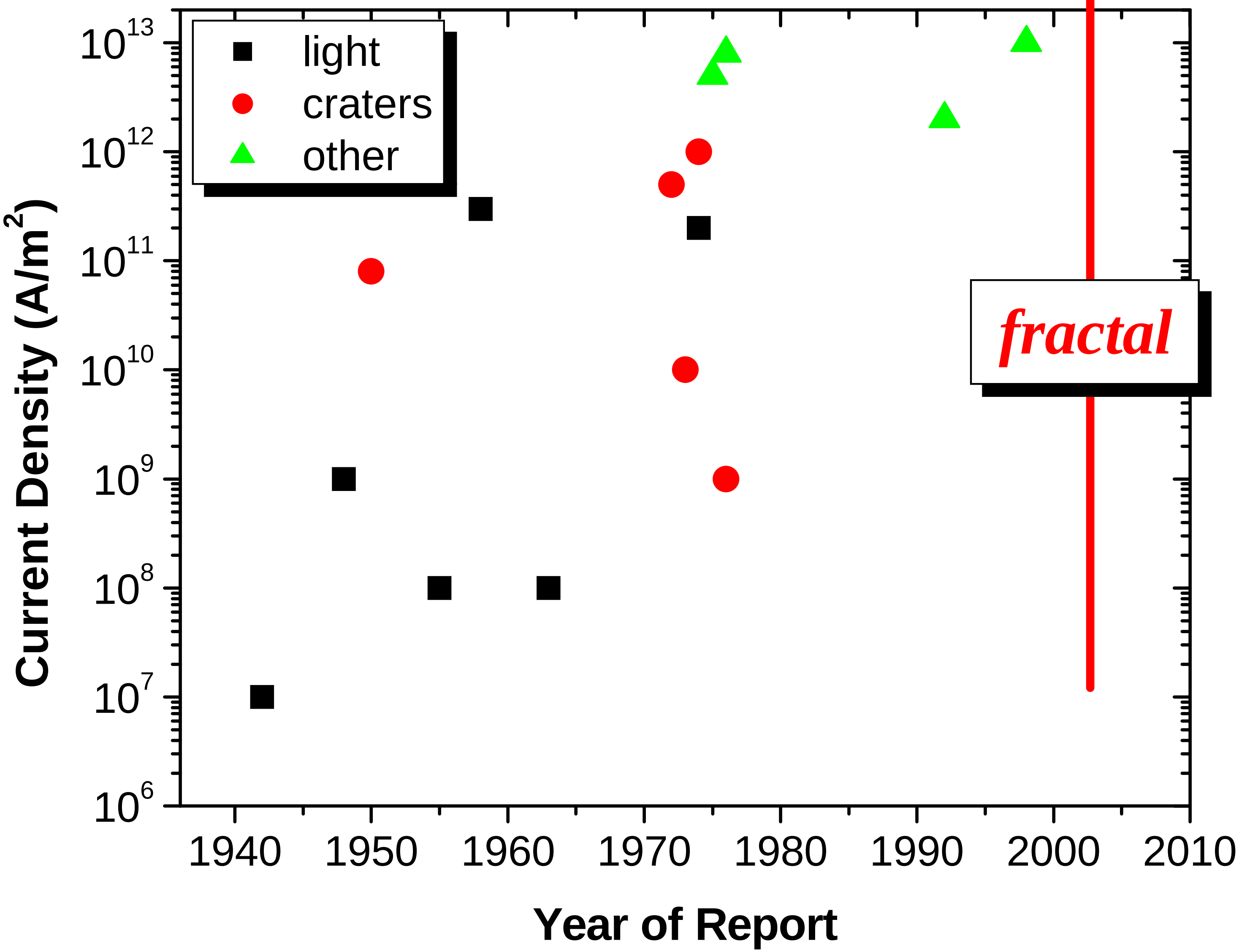
The Classic Question: How long is the coast of Britain?



The answer depends on the length scale of measurement!

B. Mandelbrot, The Fractal Geometry of Nature (1983)

New Question: What is the current density of cathode spots?



Self-Similarity

- ***An object ("fractal") is self-similar (invariant with scaling) if it is reproduced by magnifying some portion of it.***
- ***Self-similarity may be discrete or continuous, deterministic or probabilistic.***
- ***Self-similarity can be mathematically exact or only approximate and asymptotical.***

M. Schroeder, *Fractals, Chaos, Power Laws*, Freeman, New York, 2000

Fractals and Power Laws

Power laws are an abundant source of self-similarity.

The homogenous power law

$$\boxed{f(x) = cx^{\alpha}}$$

is self-similar because rescaling (multiplication with a constant) preserves that is proportional.

A fruitful approach to fractal modeling is to look for *power laws* describing the physical phenomena.

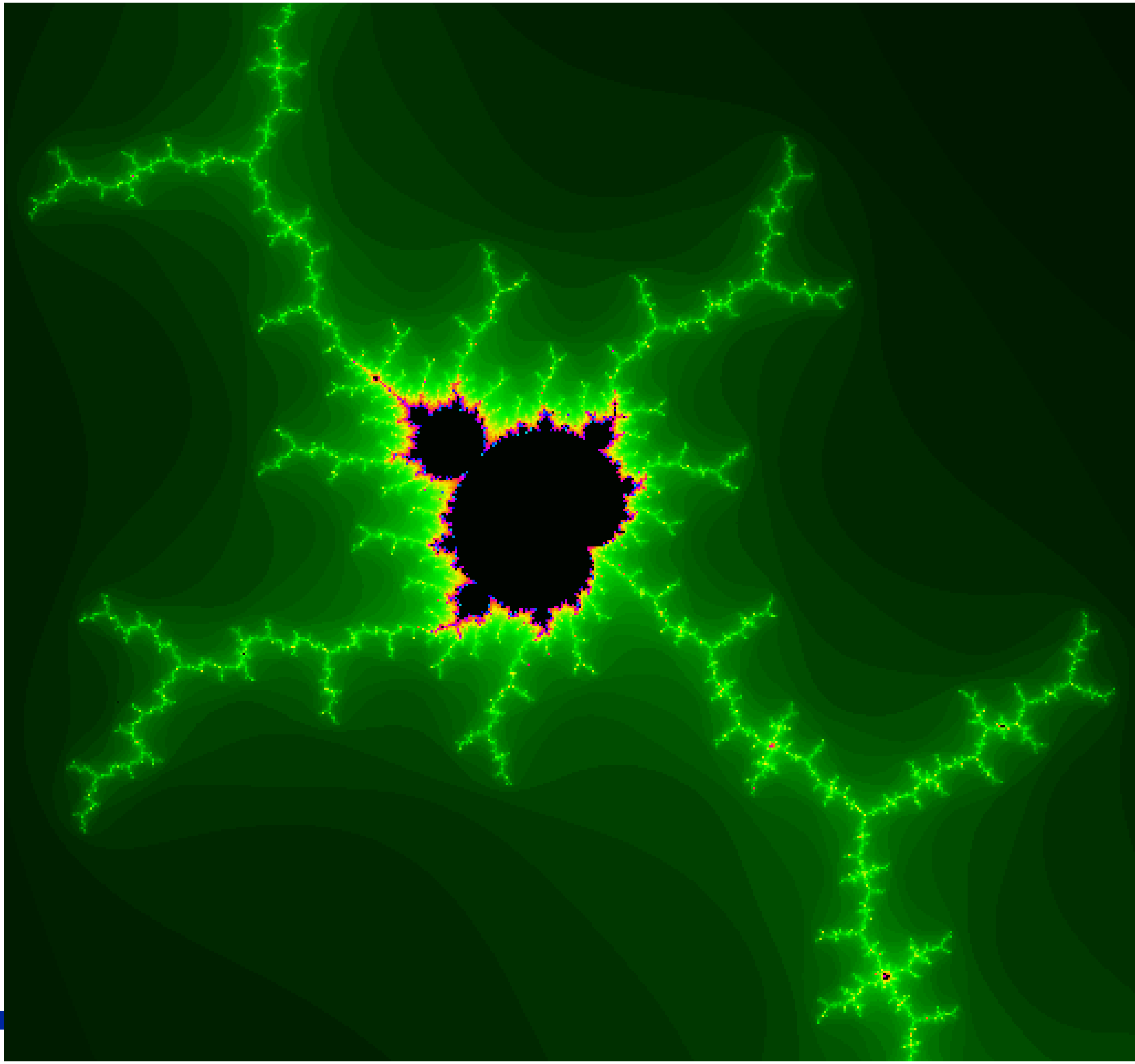
M. Schroeder, *Fractals, Chaos, Power Laws: Minutes from an Infinite Paradise* (W.H.Freeman and Company, New York, 2000).

Example of Mathematically Exact Self-Similarity

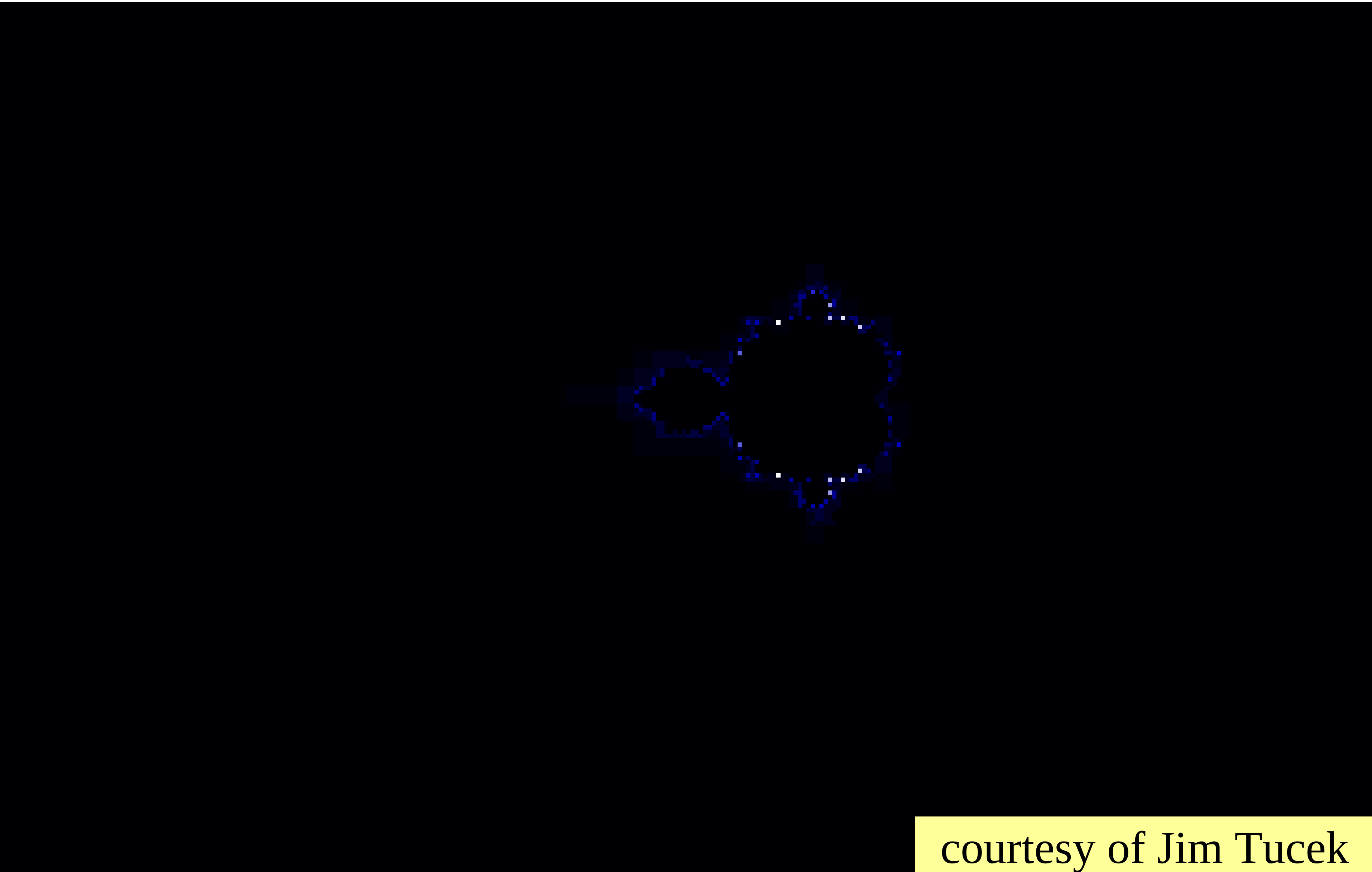
Mandelbrot-
”Lightning”

and

Mandelbrot
Trees



Example of Mathematically Exact Self-Similarity

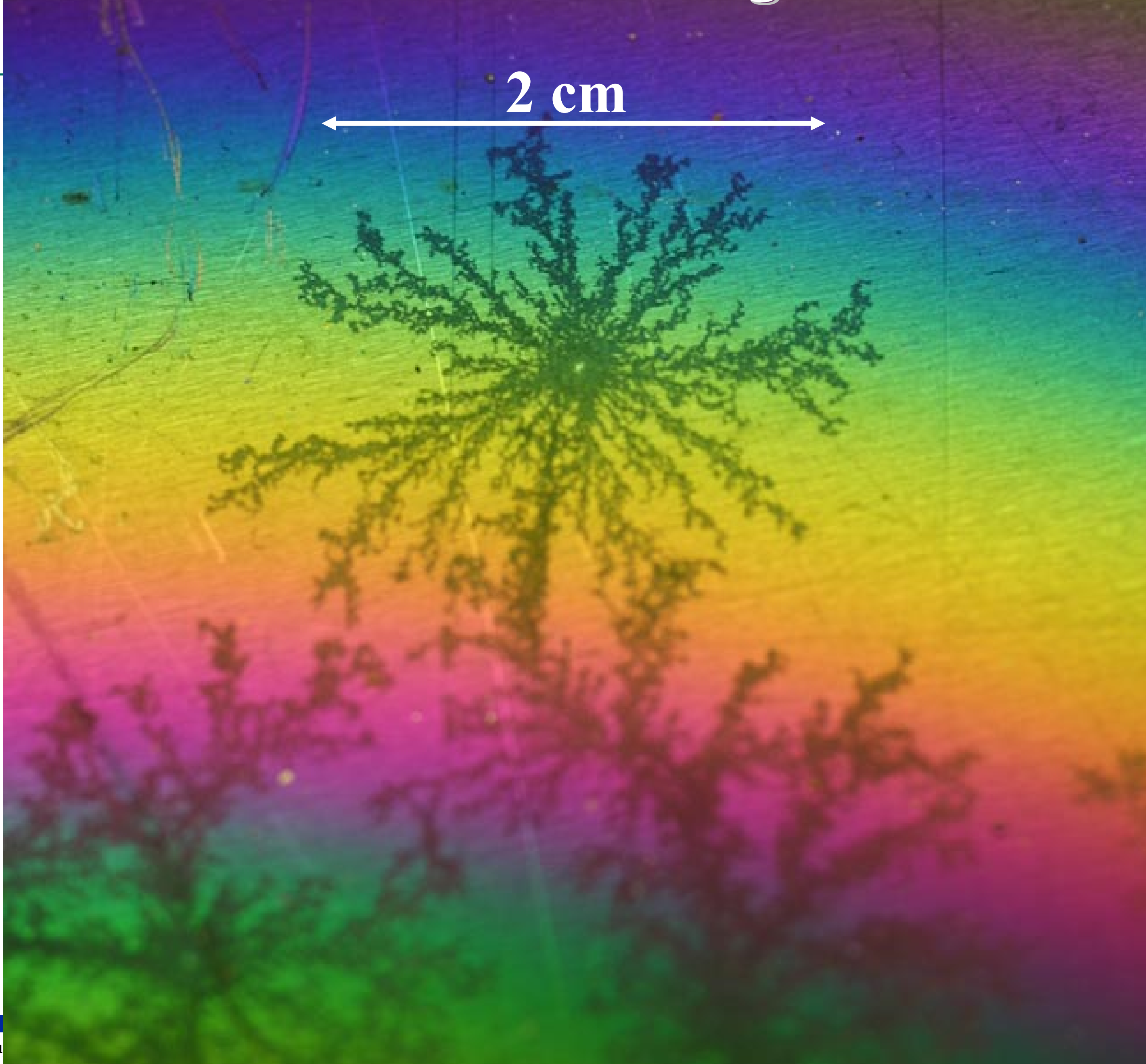


courtesy of Jim Tucek

Arc Traces – Low Magnification

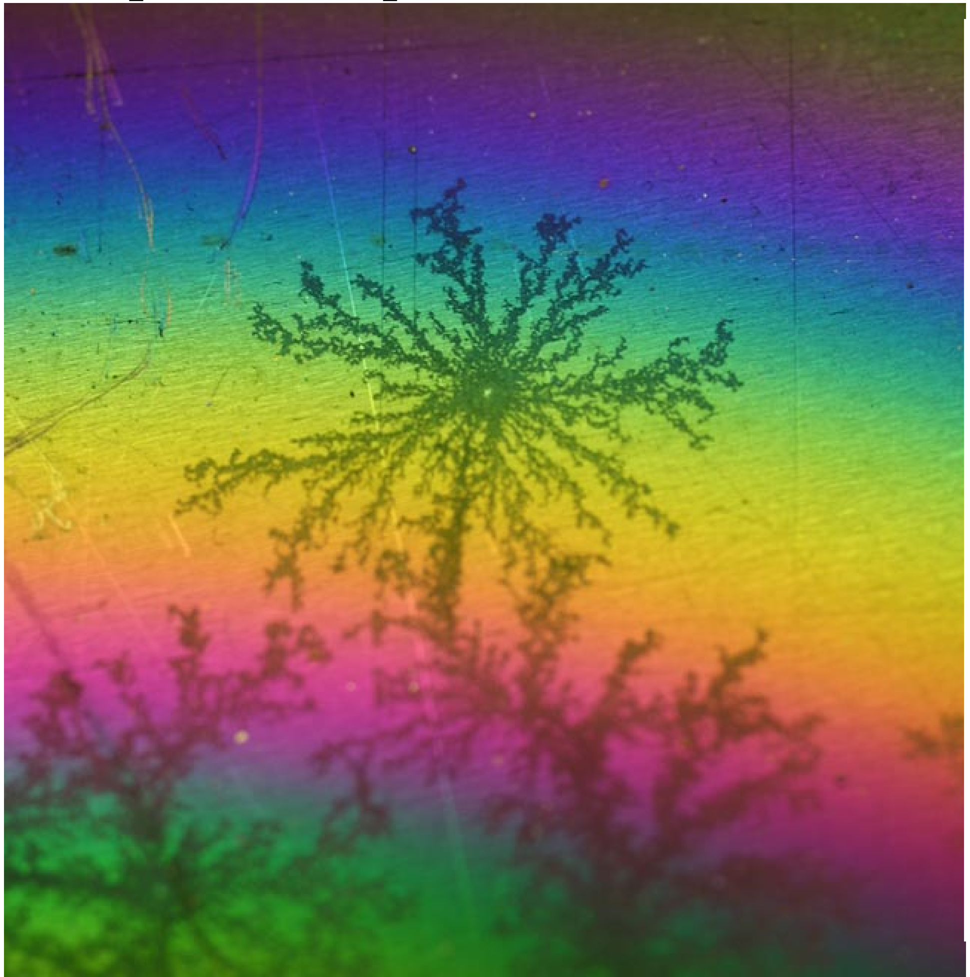
Arcing on a SS shield coated with WO_3 (colors due to interference)

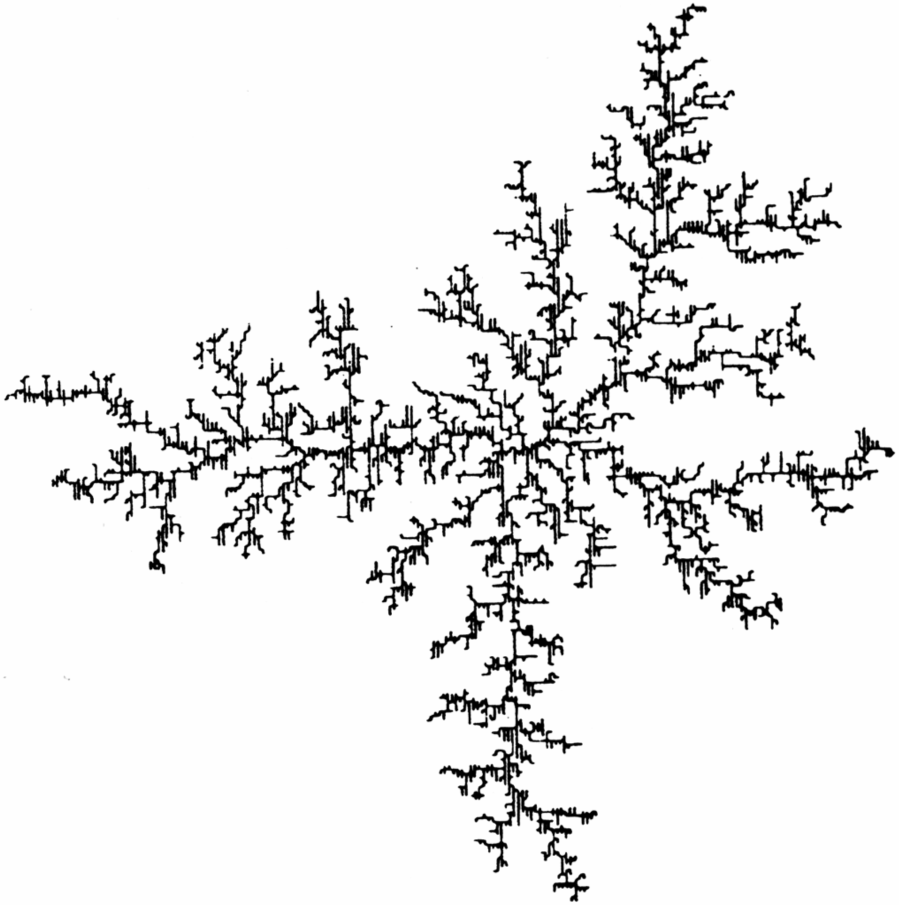
Traces are probabilistic fractal dimension ~ 1.7



Fractal Model and Ignition

- The fractal approach to "***Diffusion-limited Aggregation***" is applicable to random walk model of spot motion; ignition of a new spot corresponds to attachment of a molecule to nucleation site





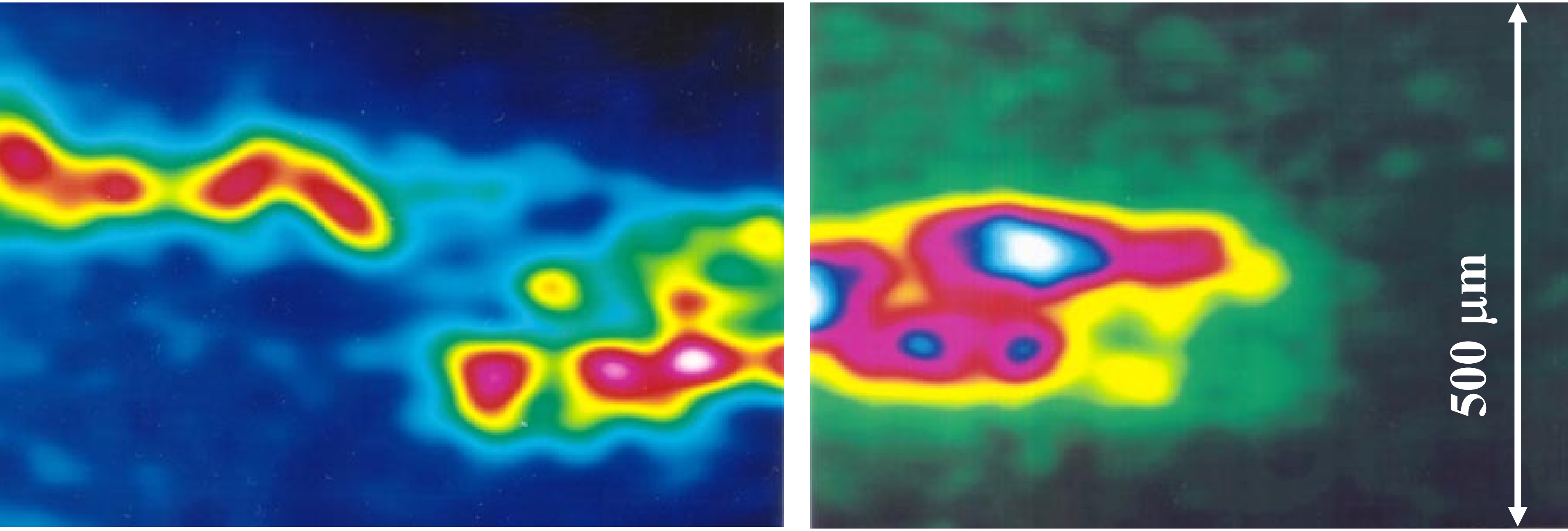
Ignition concept in Earlier History

- M.J. Druyvesteyn (1934): "*It may be that the breakdown of the insulator [layer] causes the wandering of the cathode spot of an arc in some cases.*"
- J.D. Cobine (1938): "*The discharge is influenced markedly by the condition of the copper cathode...this random variation [of the re-ignition voltage] is quite probably due to the variation in the in impurities at the cathode which influences the mechanism of arc re-ignition...*

Temporal and Spatial Self-Similarity

Streak camera pictures at different time resolution

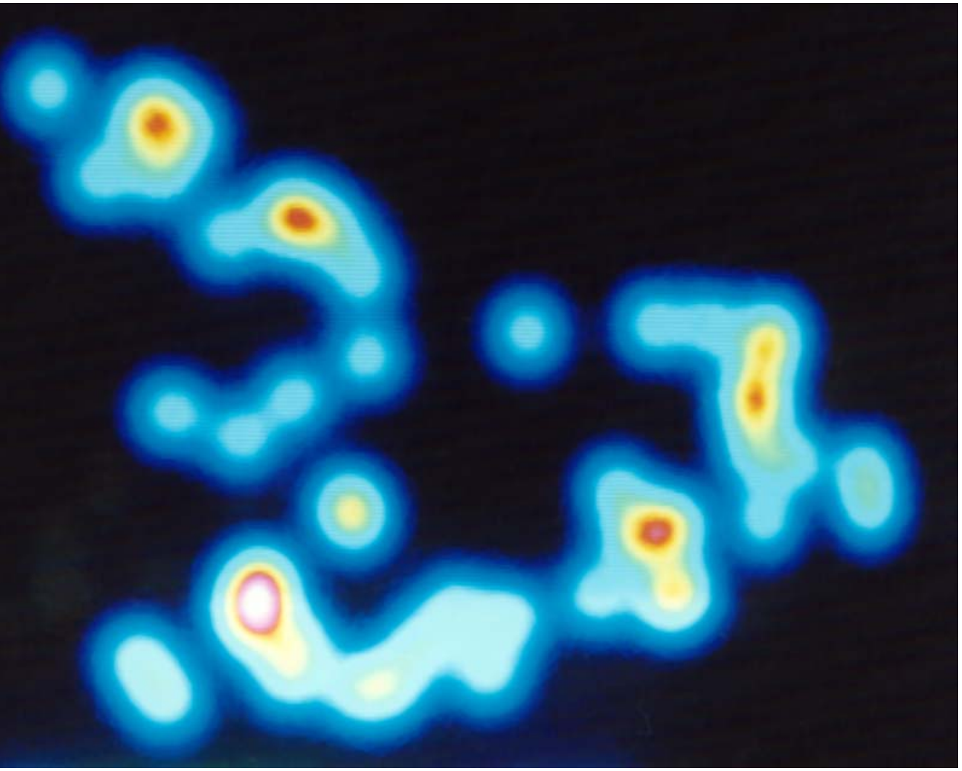
(courtesy of B. Jüttner)



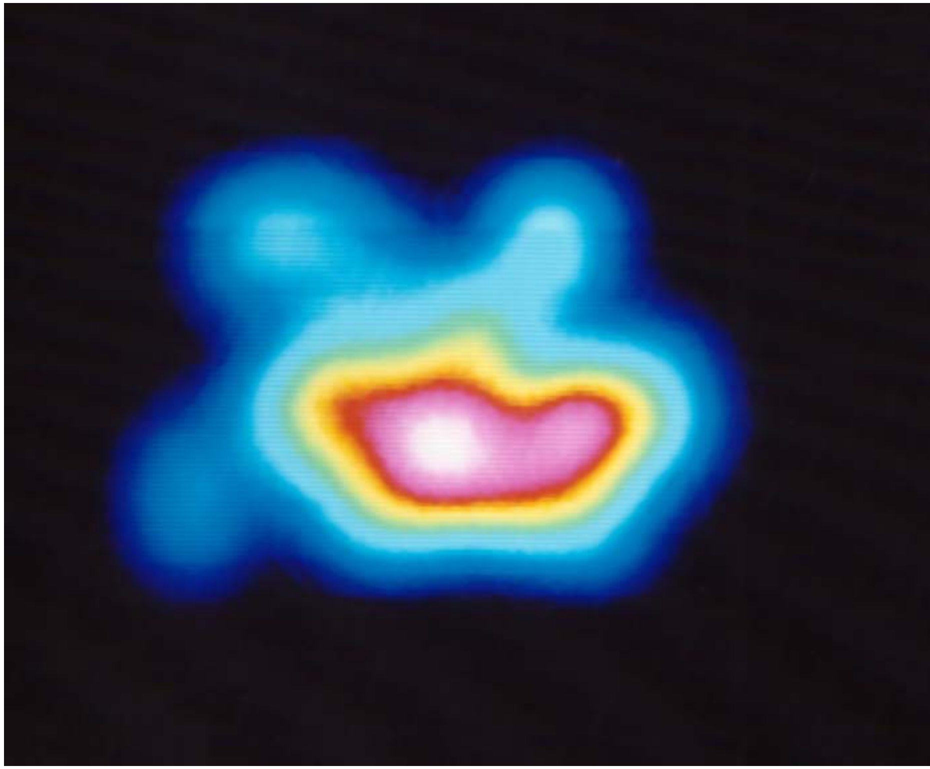
20 µs

800 ns

Simulation of Spot Light Emission



FWHM 10 μm, step=FWHM

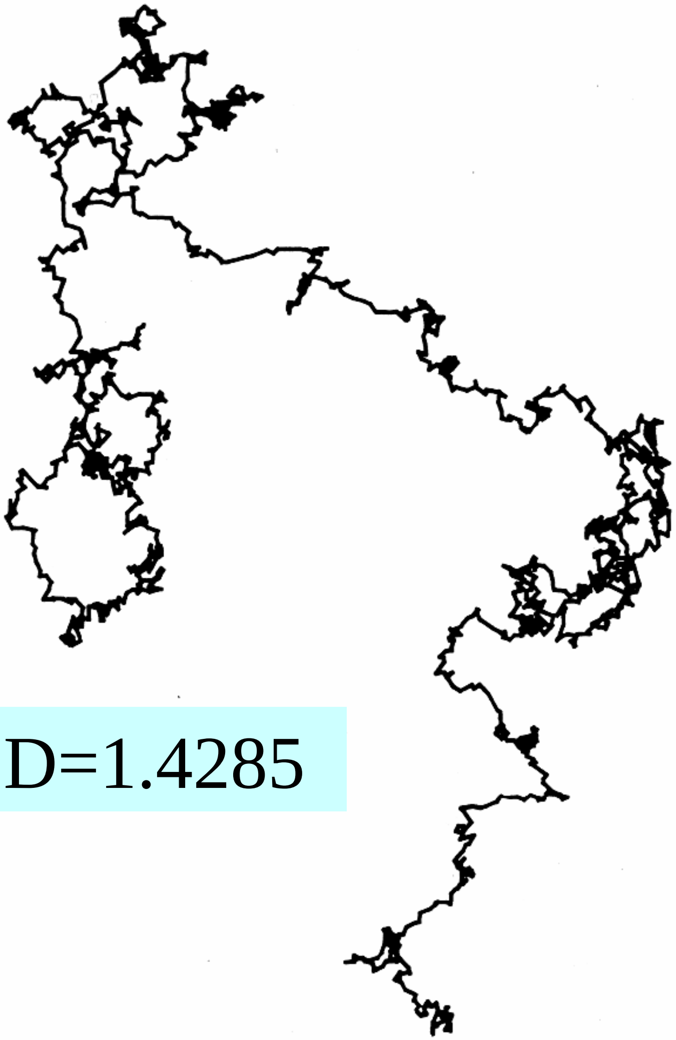


FWHM 15 μm, step=FWHM/2

Anders, et al., *J. Phys. D:* 25 (1992) 1591

Random Motion: Probabilistic Fractal

D=1.1111

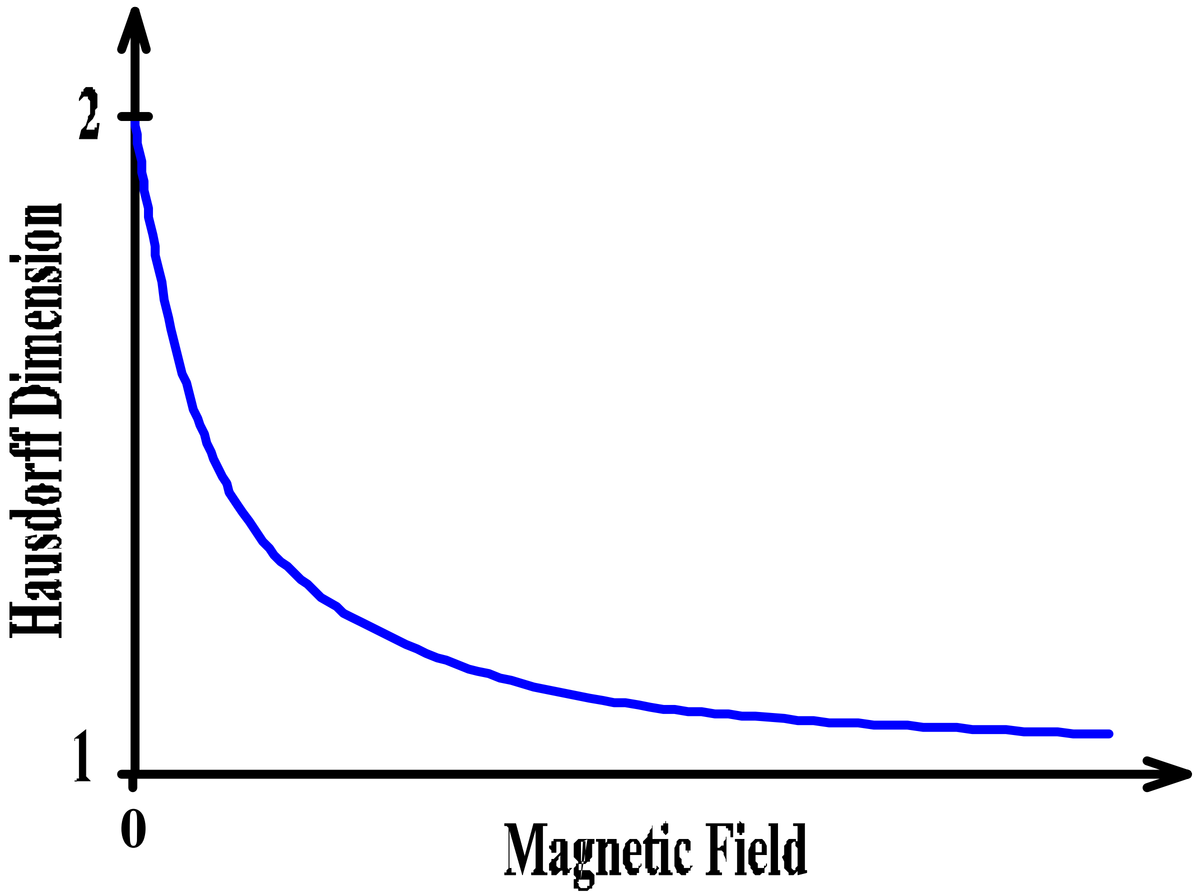


D=1.4285

B. Mandelbrot, The Fractal Geometry of Nature (1983)

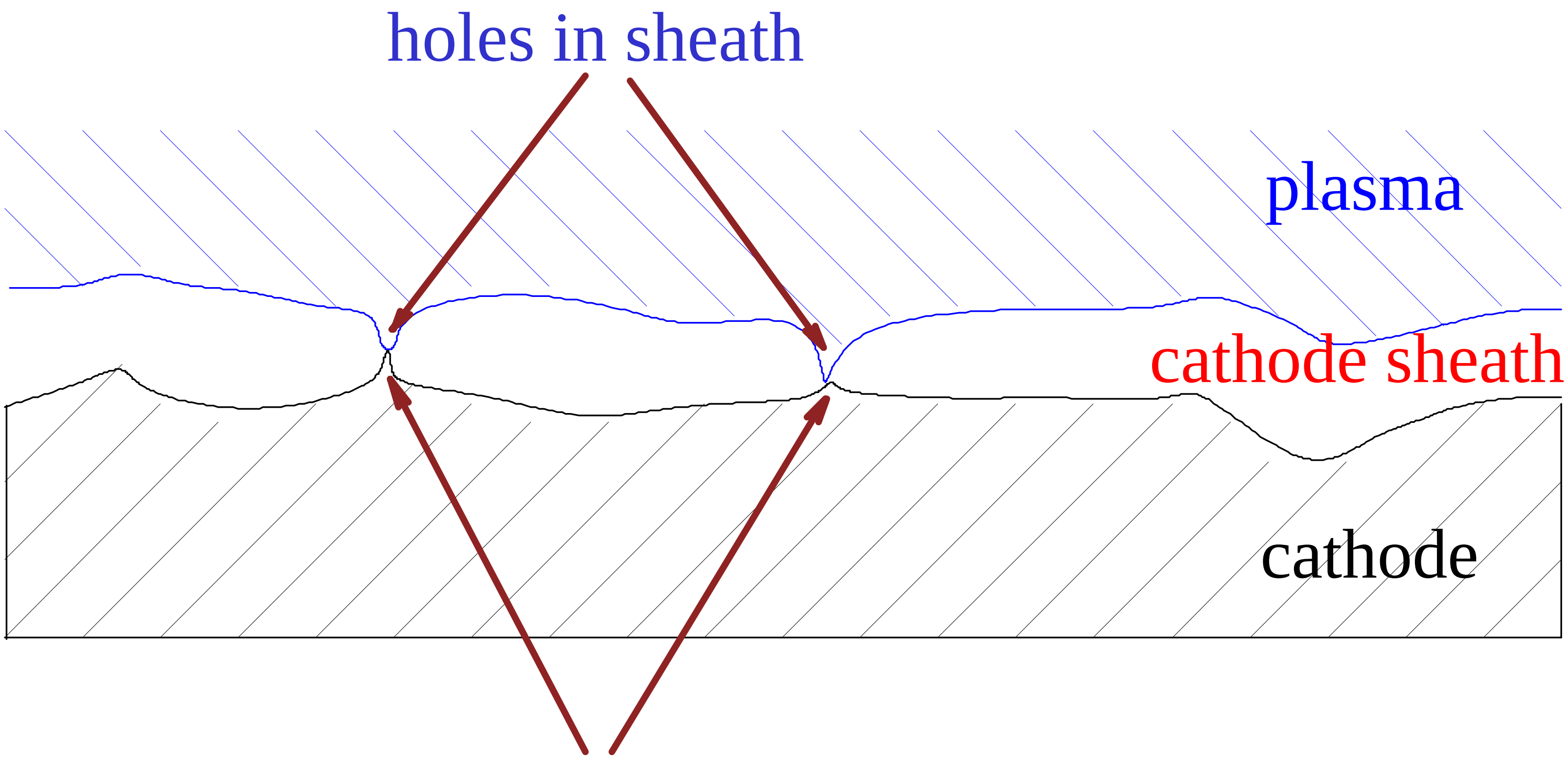
Fractal Dimension of Spot Motion

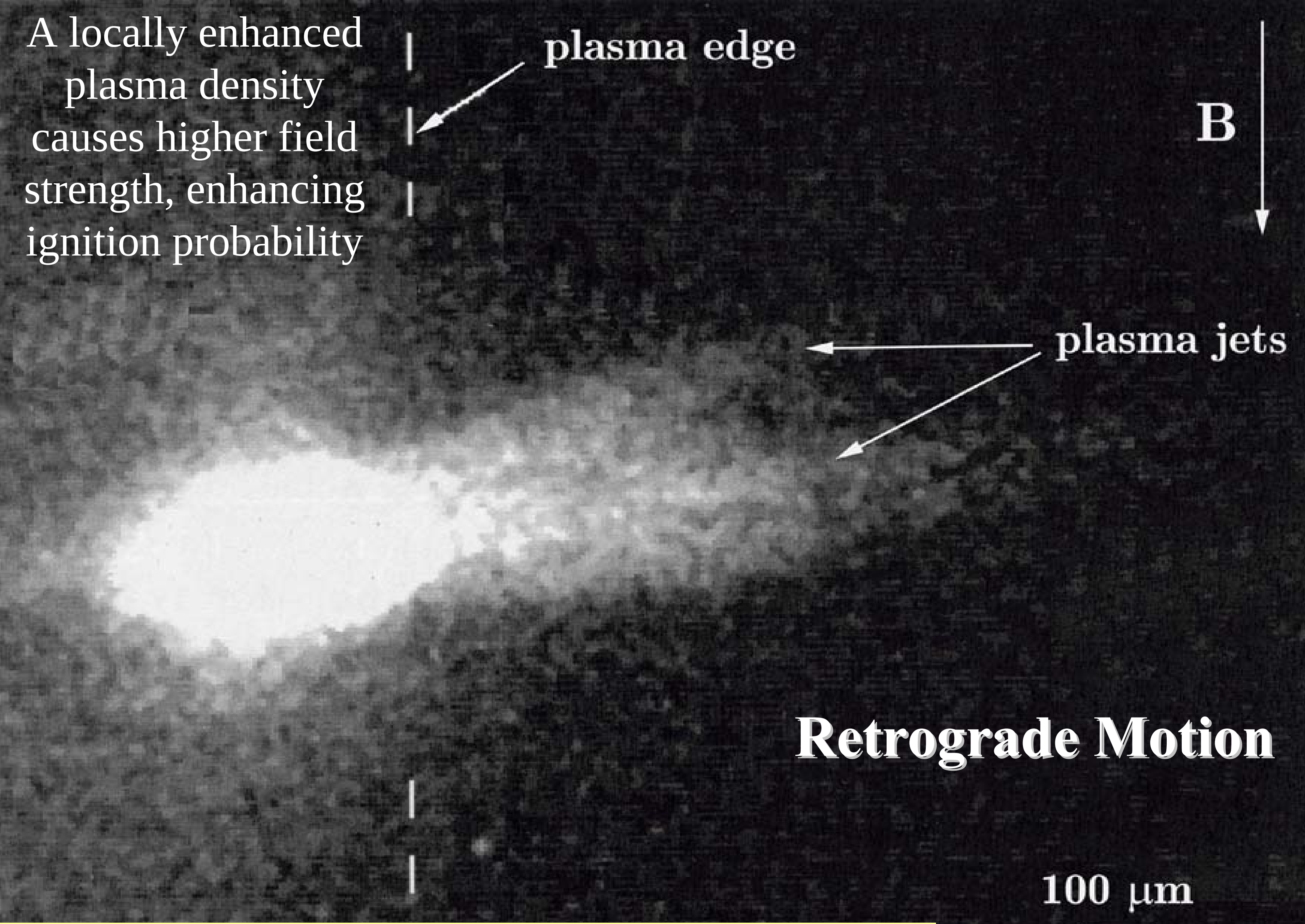
Transition from Random Motion to Steered Motion can be associated with a reduction of the fractal dimension



Fractal Sheath with "Holes"

- sheath thickness scales scales with $1/\sqrt{n}$
- no sheath but voltage drop in nonideal plasma of (exploding) emission centers: "holes" in sheath – no flux to cathode

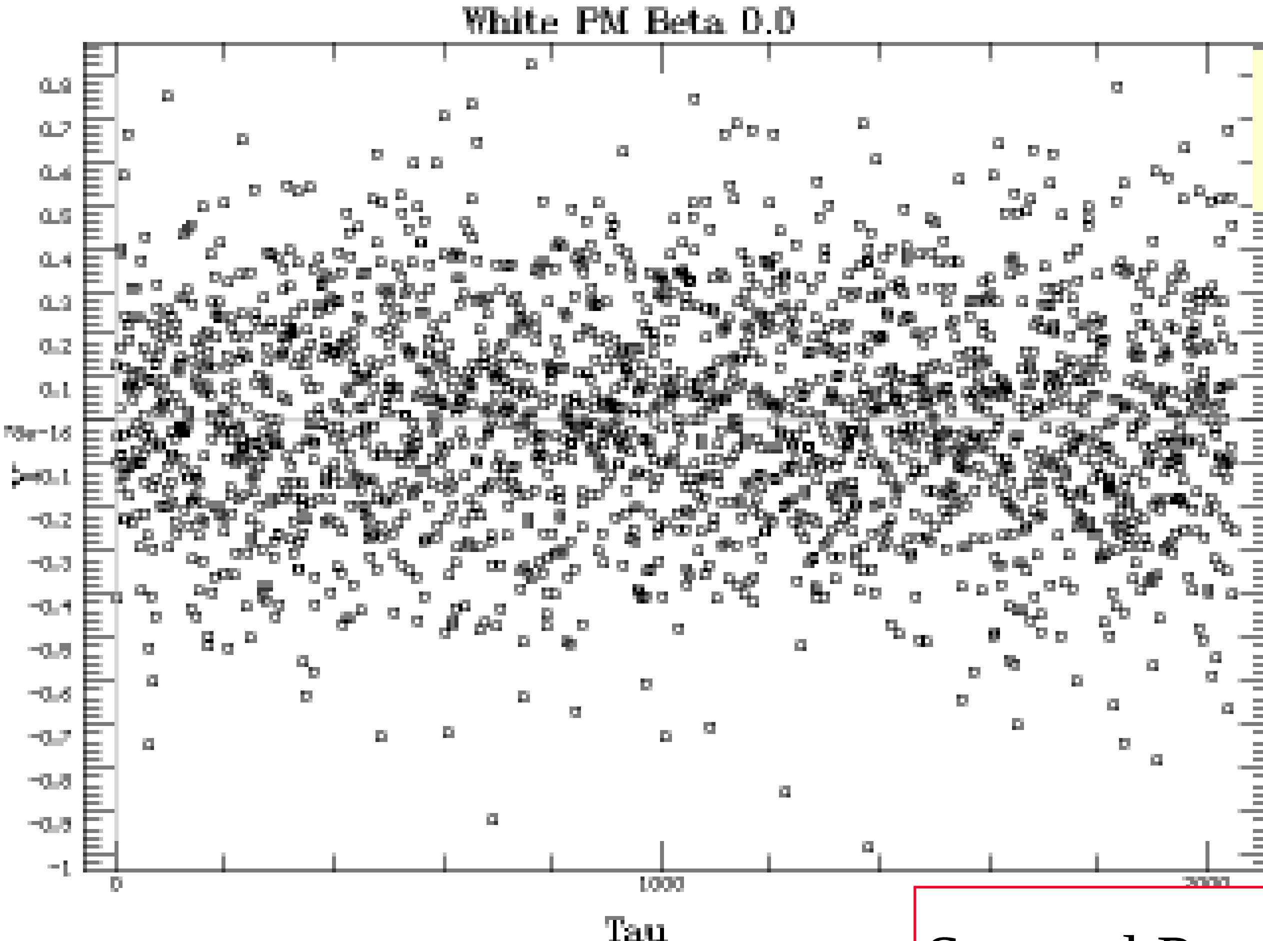




Jüttner and Kleberg, J Phys. D: Appl. Phys. **33** (2000) 2025

Noise – What Can We Learn?

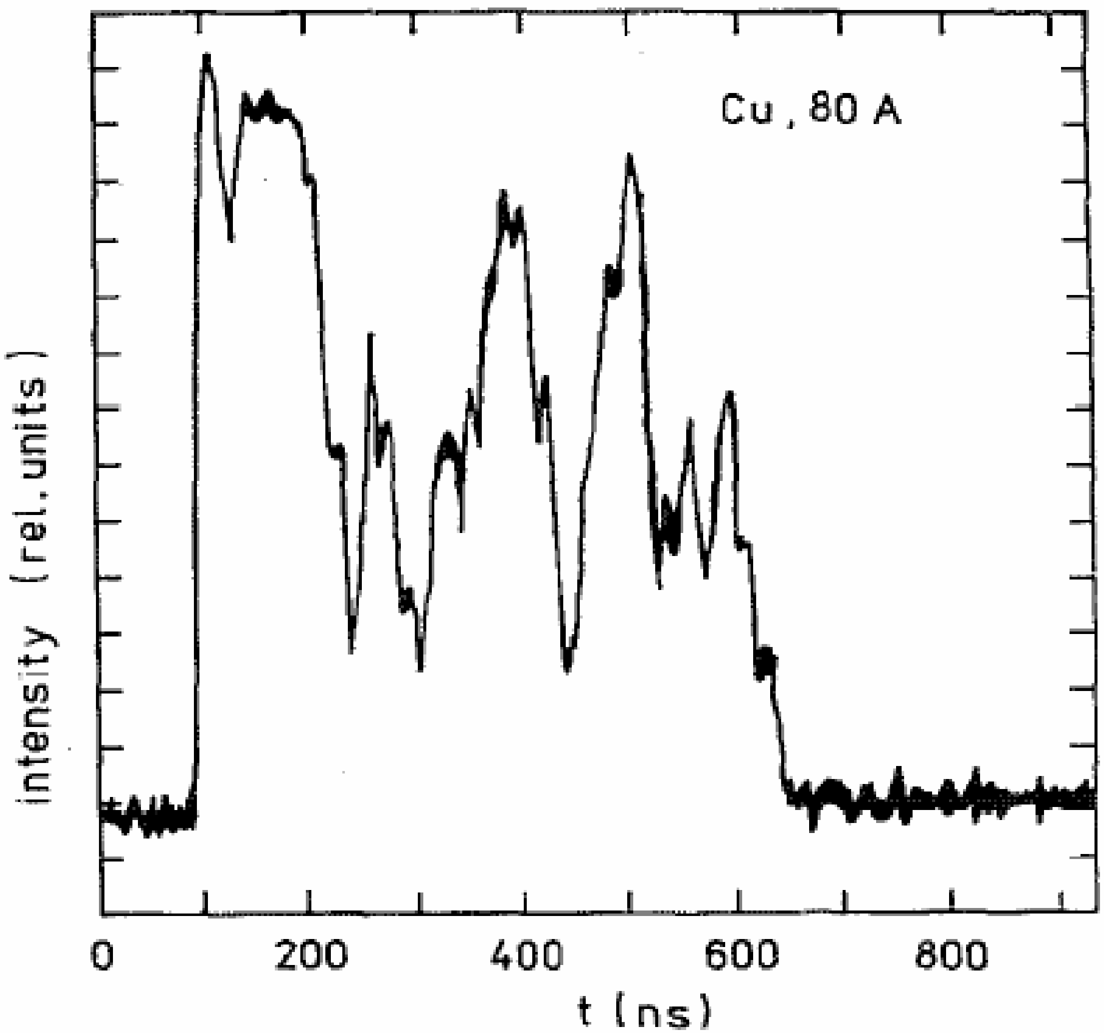
- Not all noise is equal!
- "Colored" noise (β=0 white, β=1 pink, β=2 brown, and $\beta>2$ black)



James A. DeYoung, http://tycho.usno.navy.mil/

$$\text{Spectral Power} \sim \left(FFT\left(A\right)\right)^2 \sim f^{-\beta}$$

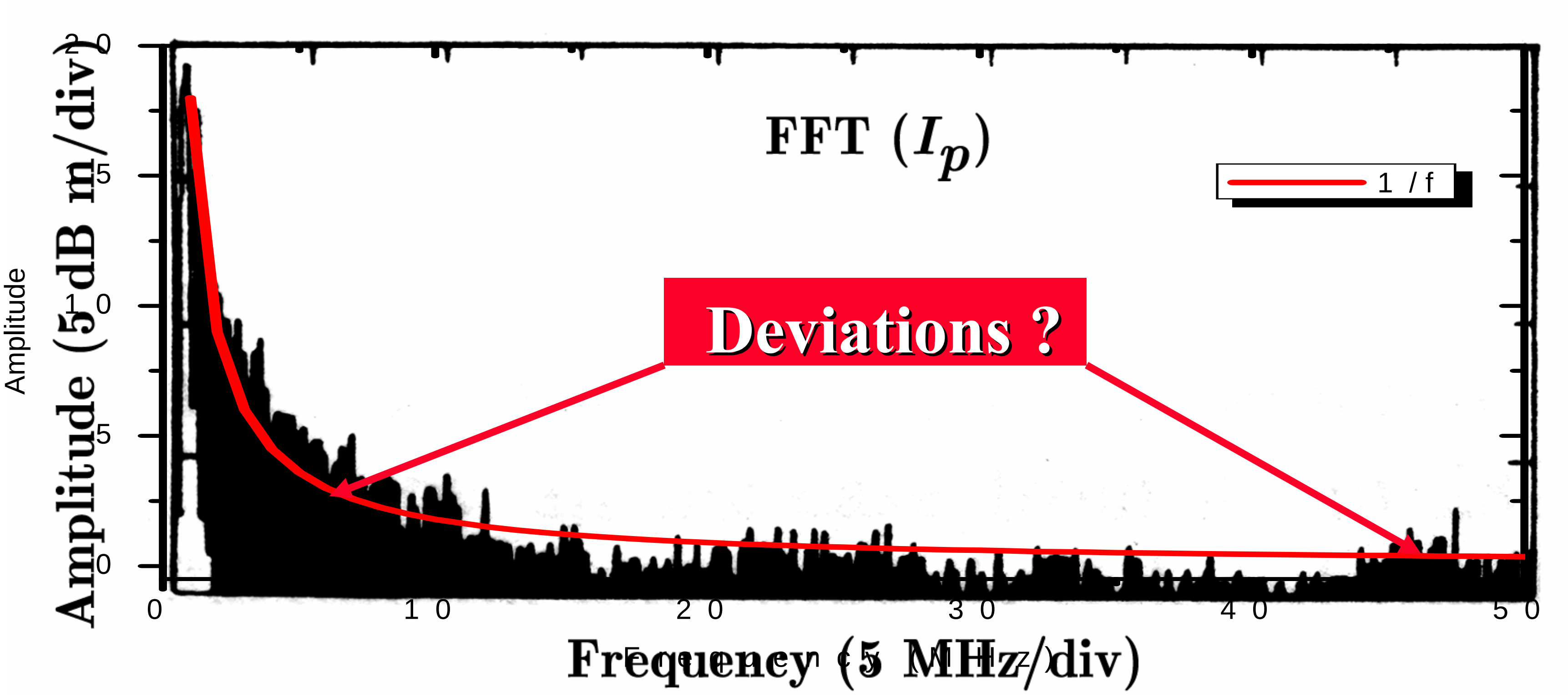
Typical "Noise" of Plasma Parameters



Anders, *et al.*, J. Phys. D **25** (1992) 1591

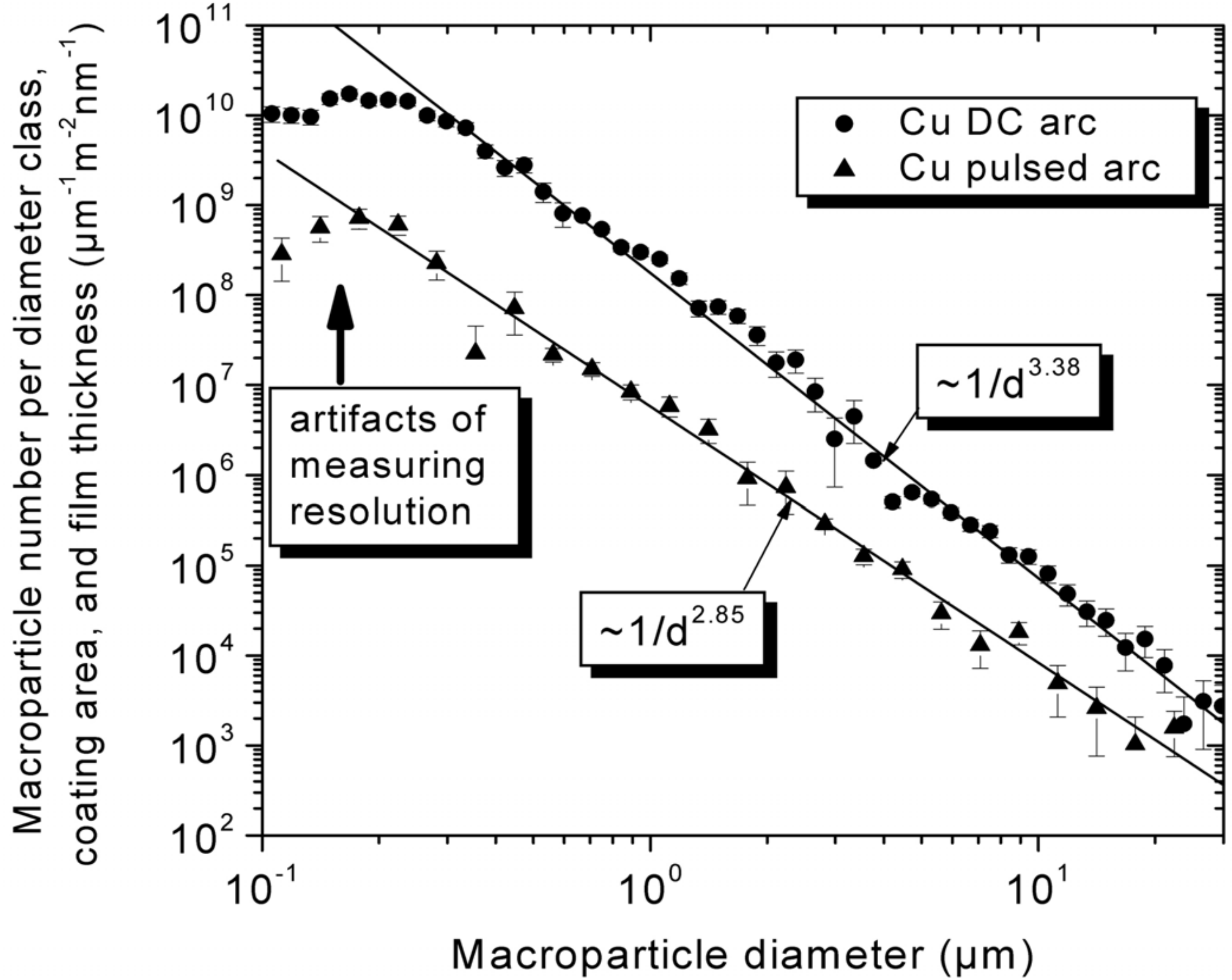
Fourier Transform Analysis

- In the limit of small current: one visible spot
- $1/f^2$ (power) noise of light & ion current for $f < 10$ MHz
- one needs to use log-log presentation to see physics



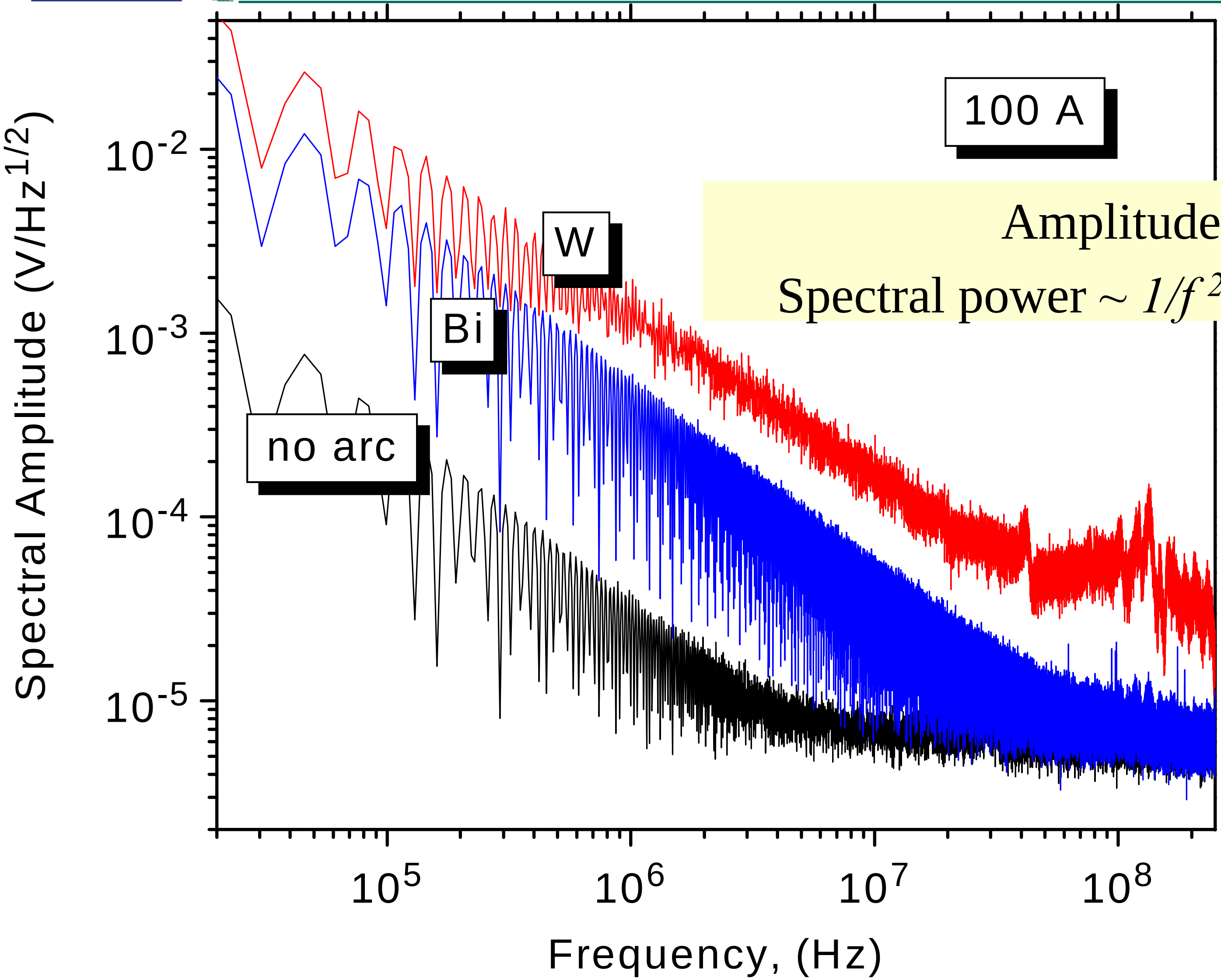
Smeets and Schulpen, J. Phys. D **21** (1988) 301c

Fractal Macroparticle Distribution



A. Anders, IEEE Trans. Plasma Sci. **33**, no.5 (2005).

Fractal Voltage

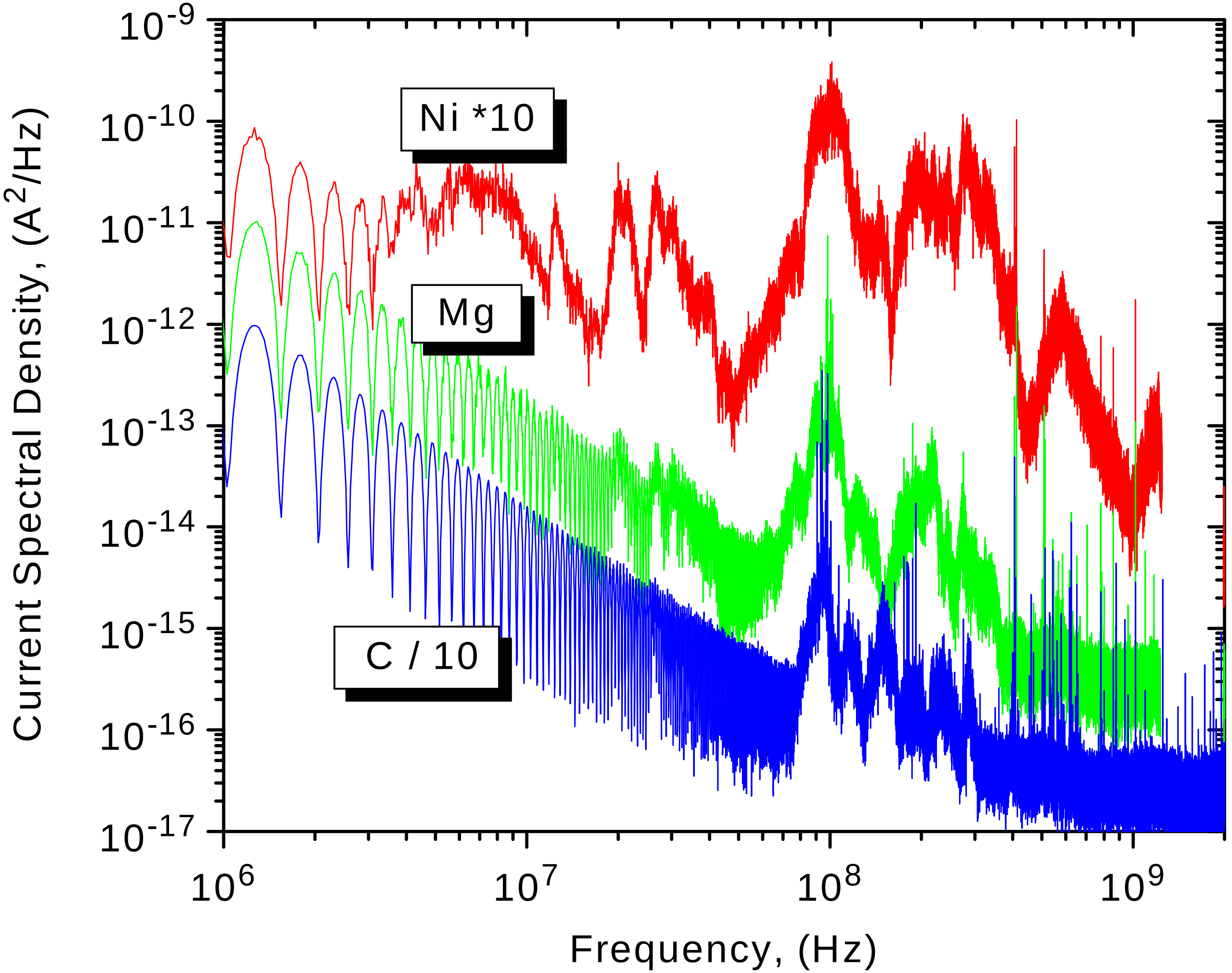


Amplitude ~ 1/*f*

Spectral power ~ *1/f* ^{2} → brown noise

A. Anders, et al., Appl. Phys. Lett. **86**, 211503 (2005).

"Ecton Cutoff" of Fractal Model



Anders and Oks, in preparation (2005).

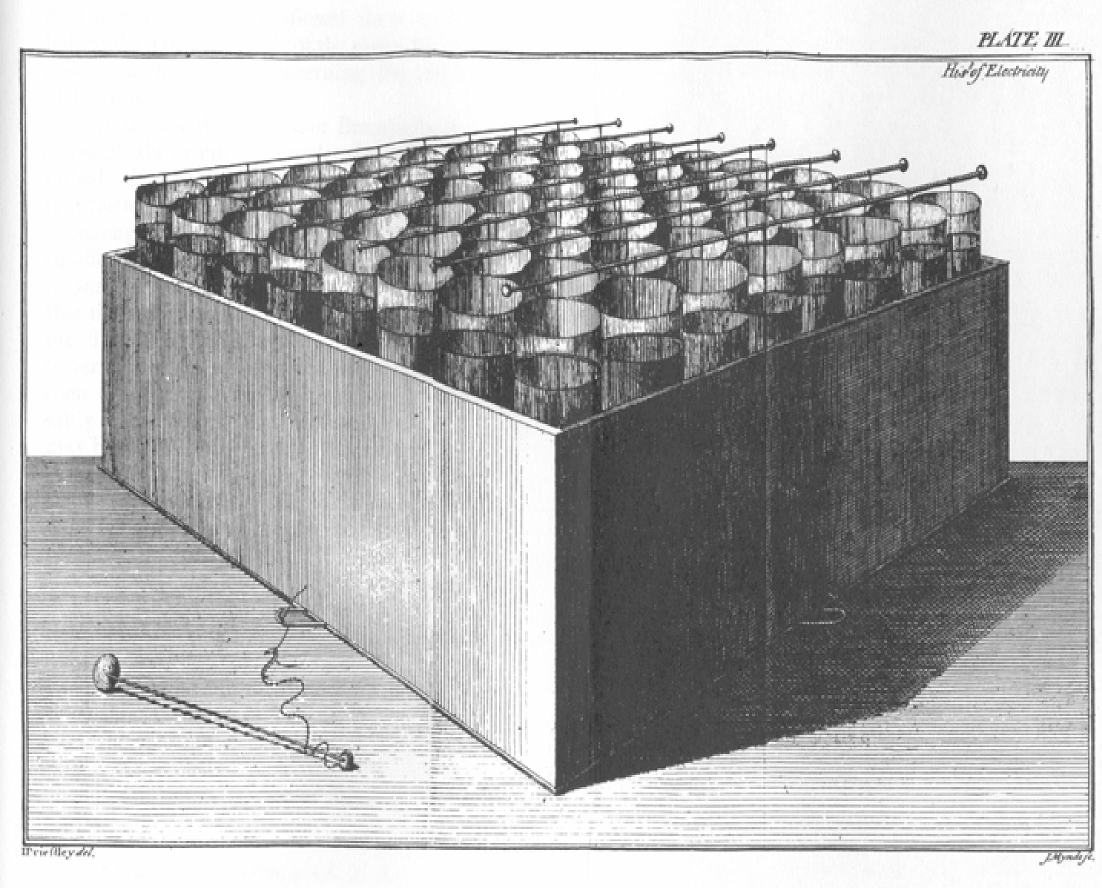
Conclusions from Fractal Concept

- Cathodic arc has many self-similar features in time and space: fractal model is not only appropriate but a means a consolidating conflicting theoretical approaches
- Numerous power laws; giving linear slope when using log-log presentation; slope ,may be interpreted as a fractal dimension for the phenomenon
- For many of the noisy parameters, the spectral density is ~ $1/f^2$, indicating “brown noise”
- Current noise shows ‘ecton peaks’ – cutoff for a physical fractal model.

History

1766 - Joseph Priestley

- First cathodic arc coating (in air)
- discharge of a bank of Leyden jars through a brass chain
- arcs between each link of the chain
- deposit on glass is well adherent
- observed Newton’s rings (oxide films)
- found black coating (copper oxide)



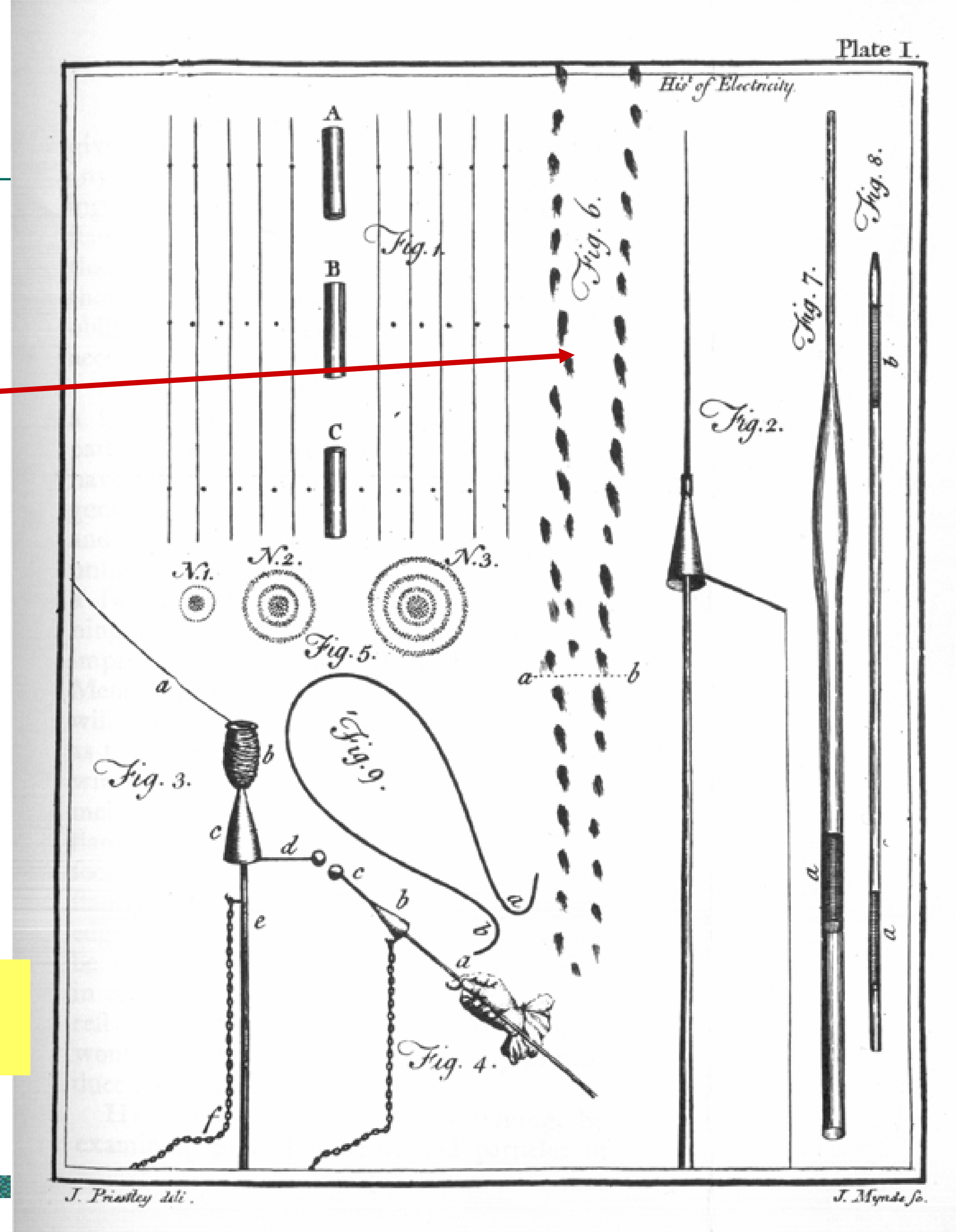
J. Priestley, *The History and Present State of Electricity*, London 1766

(on arc history) A. Anders, *IEEE Trans. Plasma Sci*. **31**, 1052 (2003)

1766 - Joseph Priestley

Cathodic arc deposition

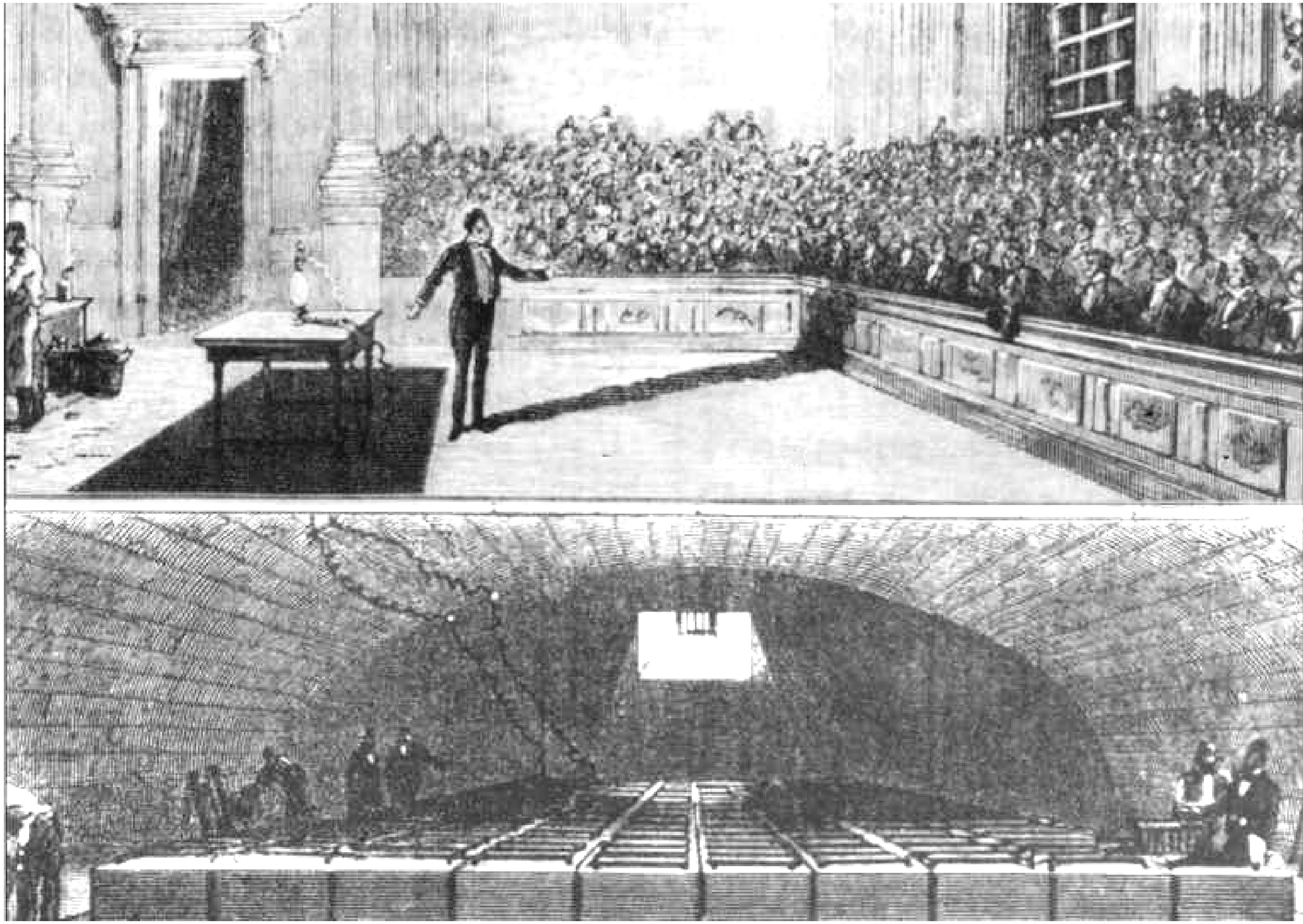
J. Priestley, The History and Present State of Electricity, London 1766



(on arc history) A. Anders, *IEEE Trans. Plasma Sci.* 31, 1052 (2003)

1802…1821 - Humphry Davy

- First short arcs in air that were fed by electrochemical battery (1802)
- Continuous arcs in air and in low-pressure vessels (1809)
- Arc demonstrations (1809?-1821)



(on arc history) A. Anders, *IEEE Trans. Plasma Sci*. **31**, 1052 (2003)

1802/03
Vasilii Petrov

- First continuous arcs in air and at low pressure using an “enormous battery” of 4200 copper-zinc plates
- published only in Russian, his work was unknown or ignored

ИЗВѢСТІЕ

О

ГАЛЬВАНИ-ВОЛЬТОВСКИХЪ

ОПЫТАХЪ,

которые производилъ

Профессоръ Физики Василій Петровъ,

посредствомъ огромной наипаче баттереи, состоявшей *иногда* изъ 4200 мѣдныхъ и цинковыхъ кружковъ, и находящейся при Санктъ-Петербургской Медико-Хирургической Академіи.

ВЪ САНКТ-ПЕТЕРБУРГѢ,

Въ Типографіи Государственной Медицинской Коллегіи, 1803 года.

(on arc history) A. Anders, *IEEE Trans. Plasma Sci.* 31, 1052 (2003)

1877 - Arthur W. Wright

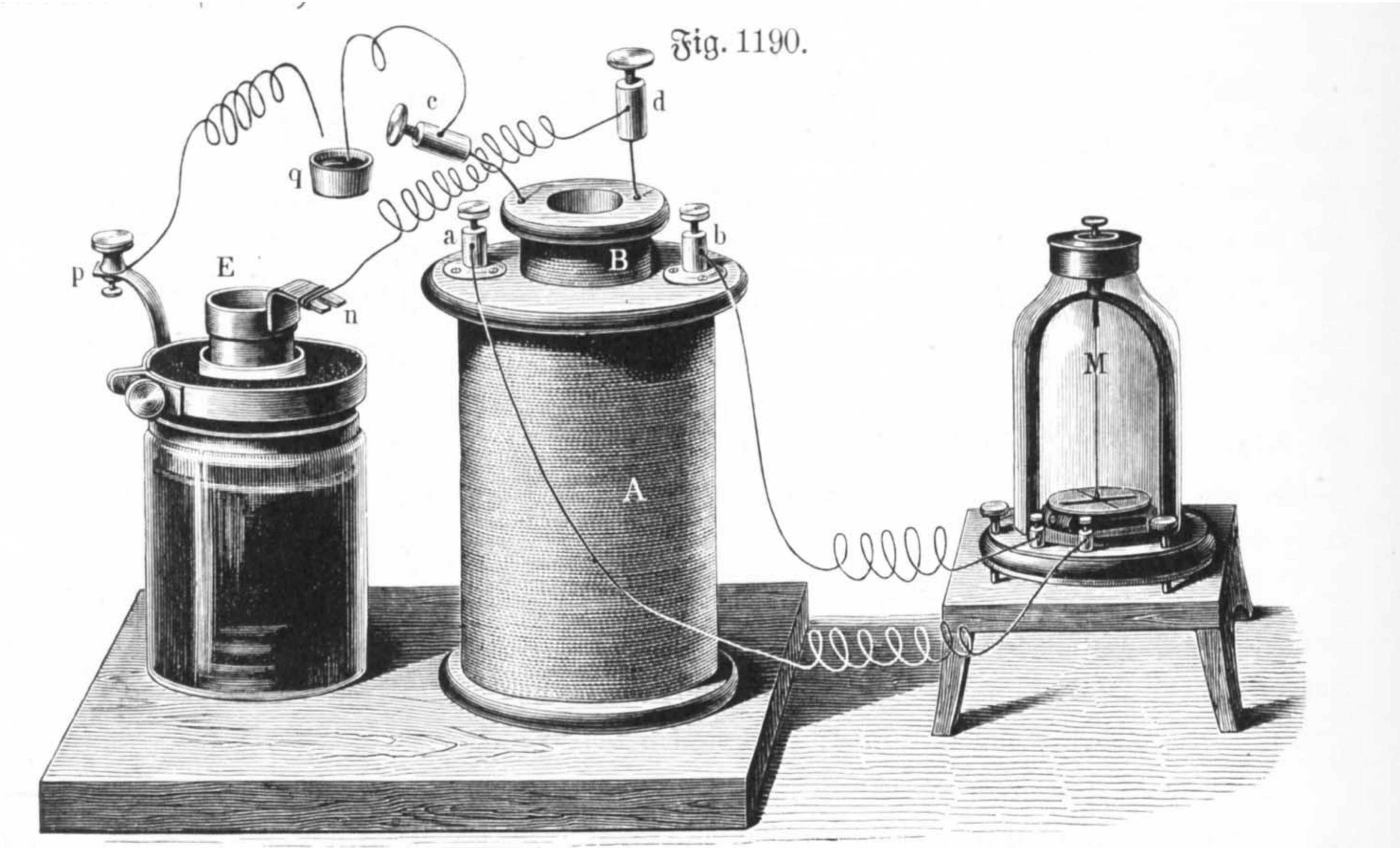
- Possibly a report on cathodic arc plasma deposition but more likely on pulsed sputtering:
  - inductive energy storage for pulsed arc
  - numerous cathode elements: Pt, Au, Co, Bi, Pd, Pb, Al, Sn, Mg, Zn , Cd, Ni, Co, Te, Fe
  - describes the different stability of films in atmosphere

(unfortunately, no figure in paper)

A.W. Wright, American J. Sci. - Third Series, vol. XIII, no. 78 (1877) 49

R.L. Boxman, IEEE Trans. Plasma Sci. 29 (2001) 759-761

1877 - Arthur W. Wright



1888-1892: Edison's phonogram patent

- First patent application granted for arc plasma deposition
- limited to *continuous* arc that (ironically) turned out to be not useful for coating of original wax phonograms

UNITED STATES PATENT OFFICE.

THOMAS A. EDISON, OF LLEWELLYN PARK, NEW JERSEY, ASSIGNOR TO THE EDISON PHONOGRAPH COMPANY, OF NEW JERSEY.

PROCESS OF DUPLICATING PHONOGRAMS.

SPECIFICATION forming part of Letters Patent No. 484,582, dated October 18, 1892.

Original application filed January 5, 1888, Serial No. 259,896. Divided and this application filed January 30, 1888. Renewed March 30, 1892. Serial No. 427,011. (No specimens.)

To all whom it may concern:

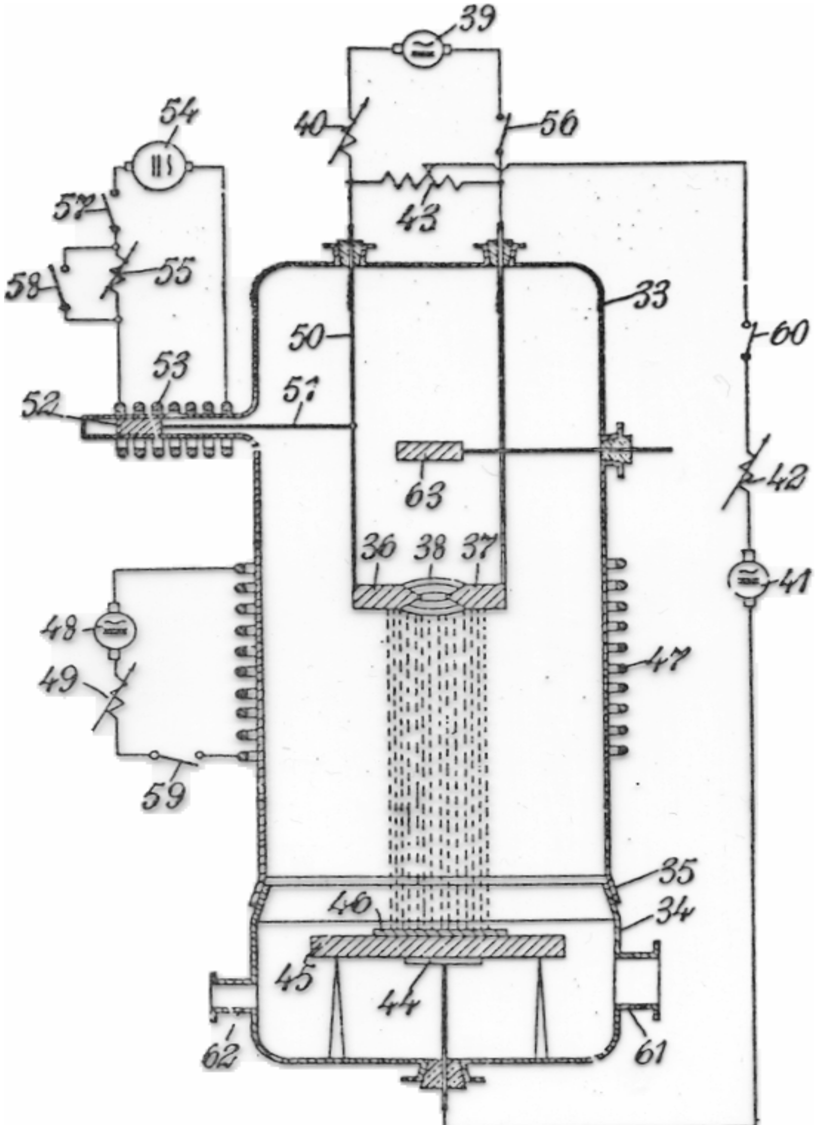
Be it known that I, THOMAS A. EDISON, of Llewellyn Park, in the county of Essex and State of New Jersey, have invented a certain new and useful Process for Duplicating Phonograms, (Case No. 751,) of which the follow-

covered by a more rapid process to give strength and body to the covering. A further covering of metal may be produced by electroplating a metal upon the vacuous deposit in the usual manner of electroplating, or the vacuous deposit may be backed up by

Inventor
Thomas A. Edison,

By his Attorneys
Dyer & Seely

1939 - Burkhardt and Reinecke



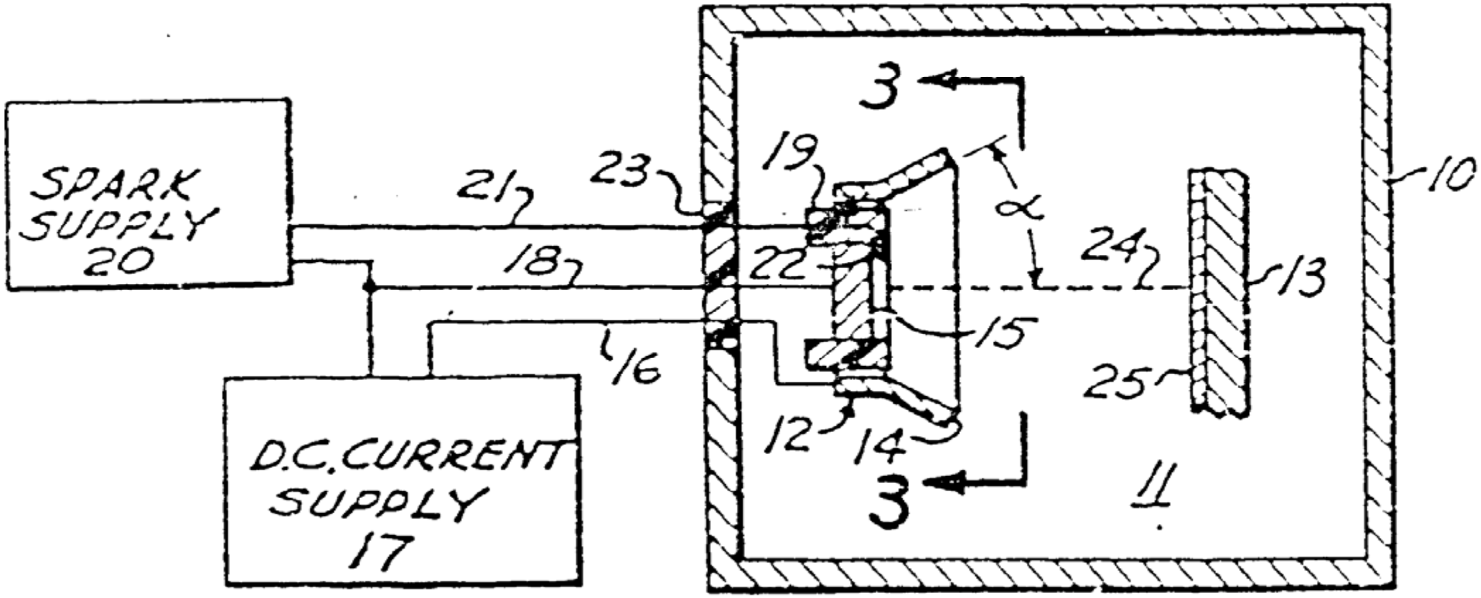
- Consumable electrodes deposited film onto biased or unbiased substrates.

W. Burkhardt and R. Reinecke,
US 2,157,478: Method of coating articles by vaporized coating materials.

1971 - Snaper

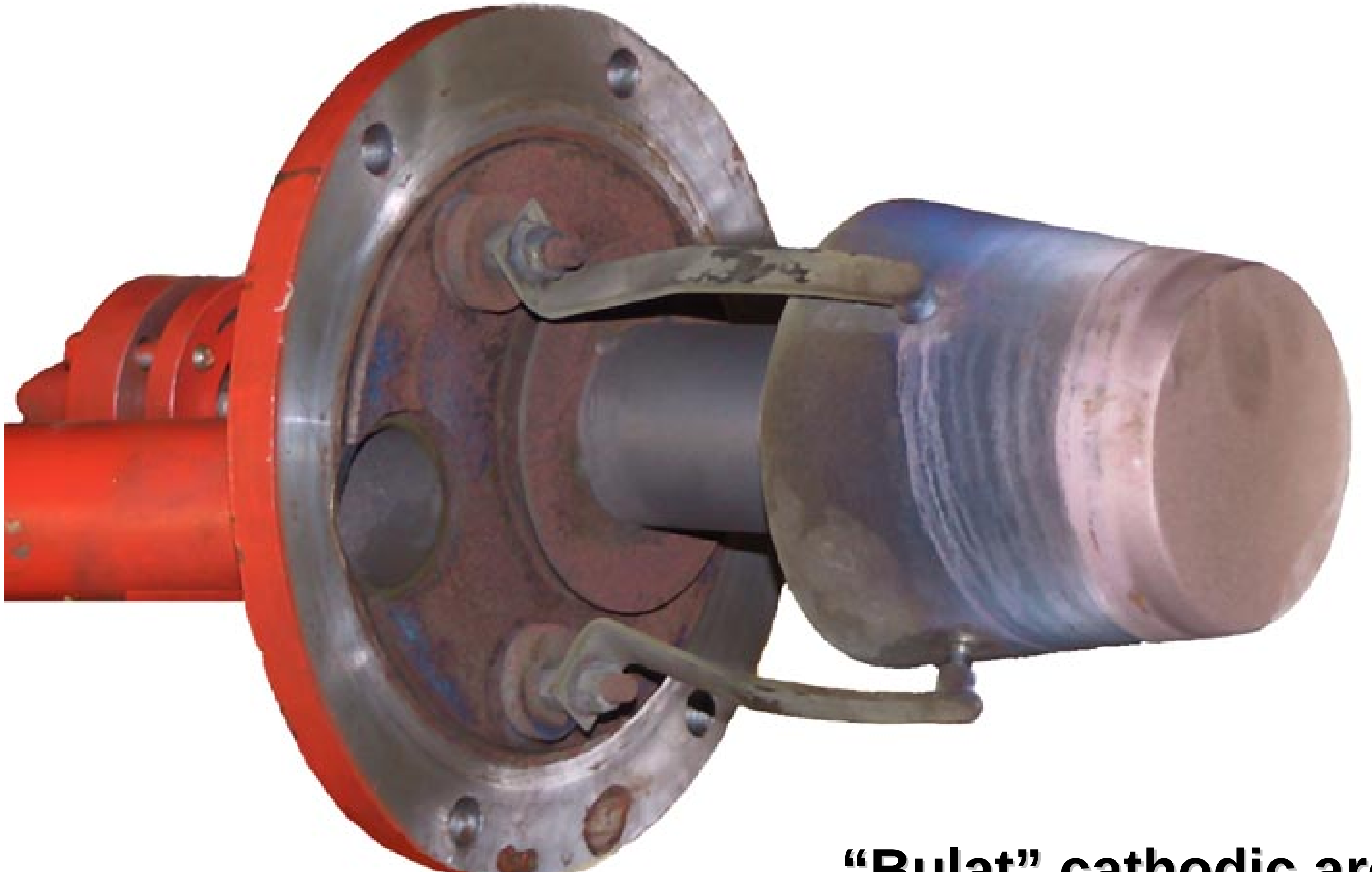
- Arc deposition process and apparatus.
- Cathodic arc source incorporated into a single devise.
- Insulator arc travel confinement.
- Line-of-sight process.
- Discrete anode (not chamber).

A.A. Snaper, (1974).
US 3,625,848: Arc deposition process and apparatus.



Soviet Union in 1970s

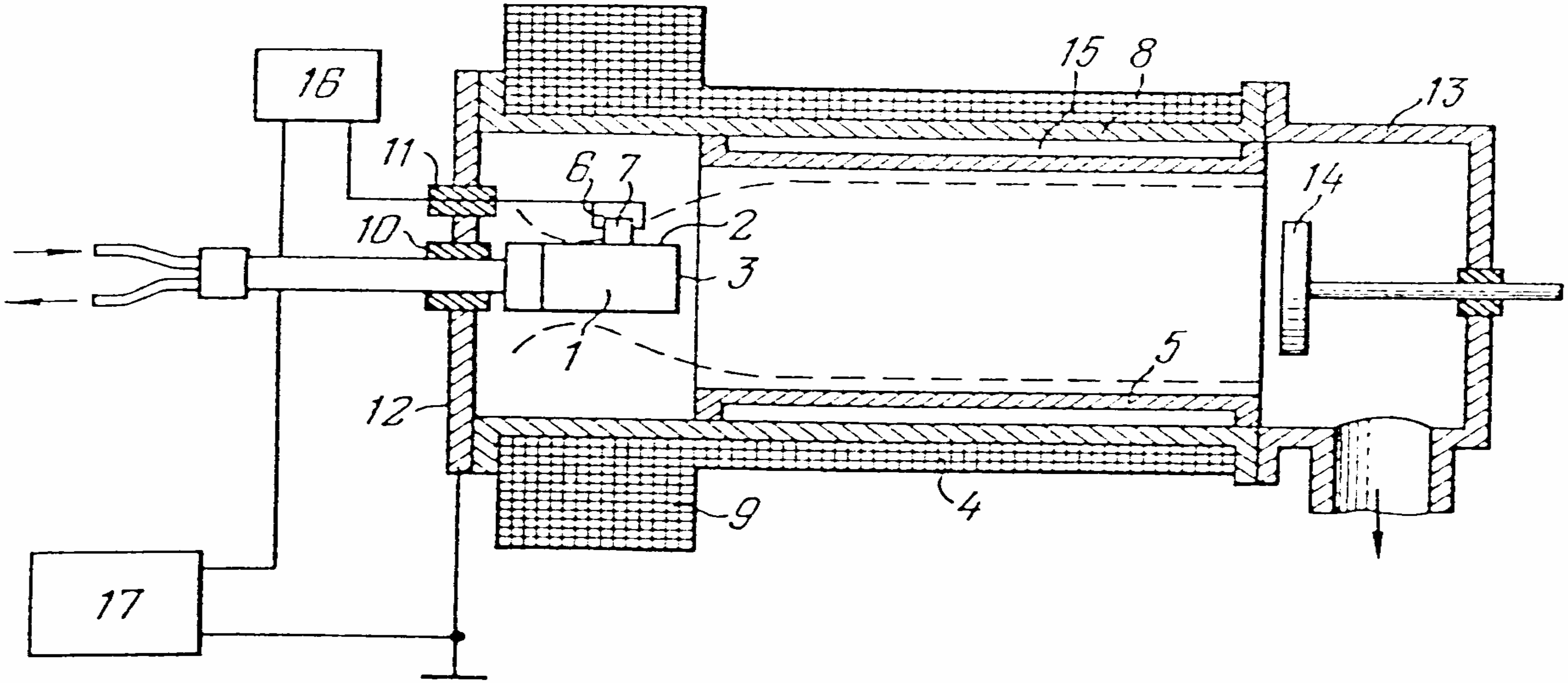
- State-run development of eventually 10,000 arc source



"Bulat" cathodic arc source

1978, 1985 - Axenov et al.

- First major use of magnetic field control of coating particles leading the way to curvilinear devices for macroparticle control.
- Arc confinement on cathode face with magnetic fields.
- Chamber as anode.
- Line-of-sight process, and also non-line-of-sight processes.



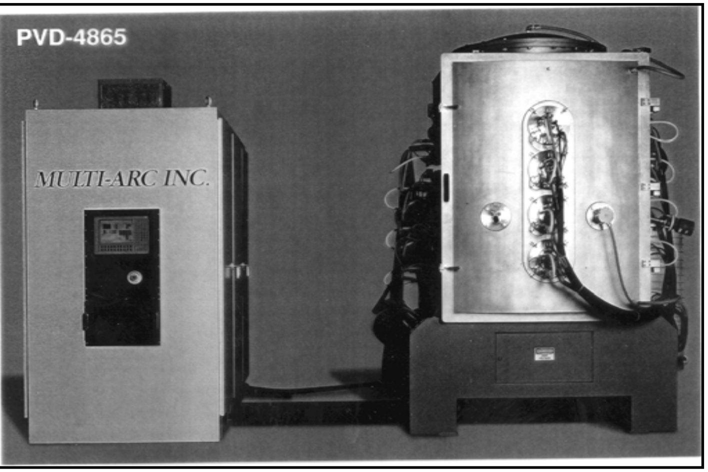
Arc Plasma Sources & Macroparticle Filters

DC Arc Source : Steered Arc

movie

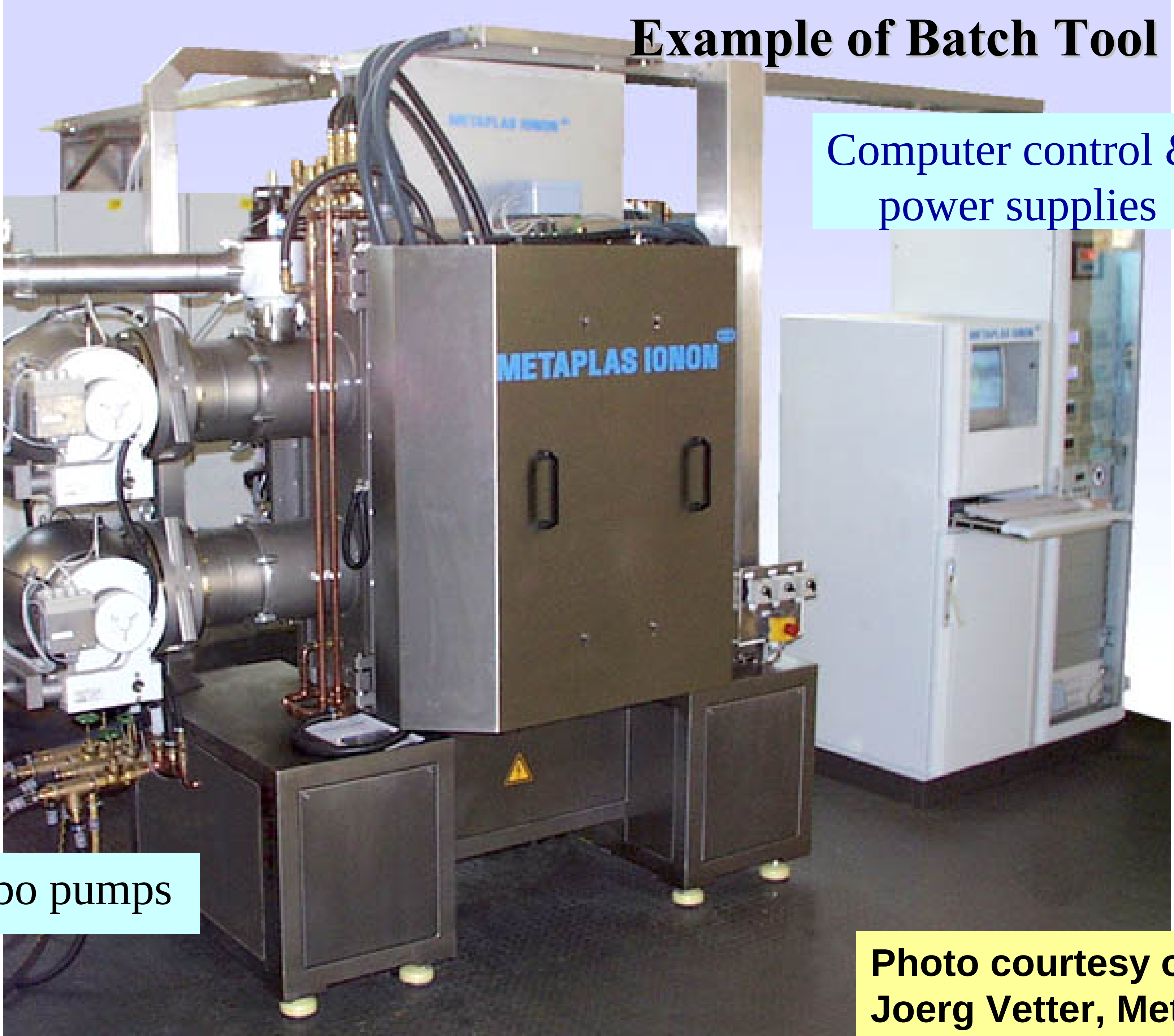
Batch versus Linear Processing

- Batch Systems
  - *low to moderate production volume*
  - *lower cost to manufacture*
  - *good cycle to cycle inspection and maintenance of sources and inner chamber components (liners)*
  - *greater operator interface handling substrates*



Ion Bond   Hauser   Vergason

Example of Batch Tool

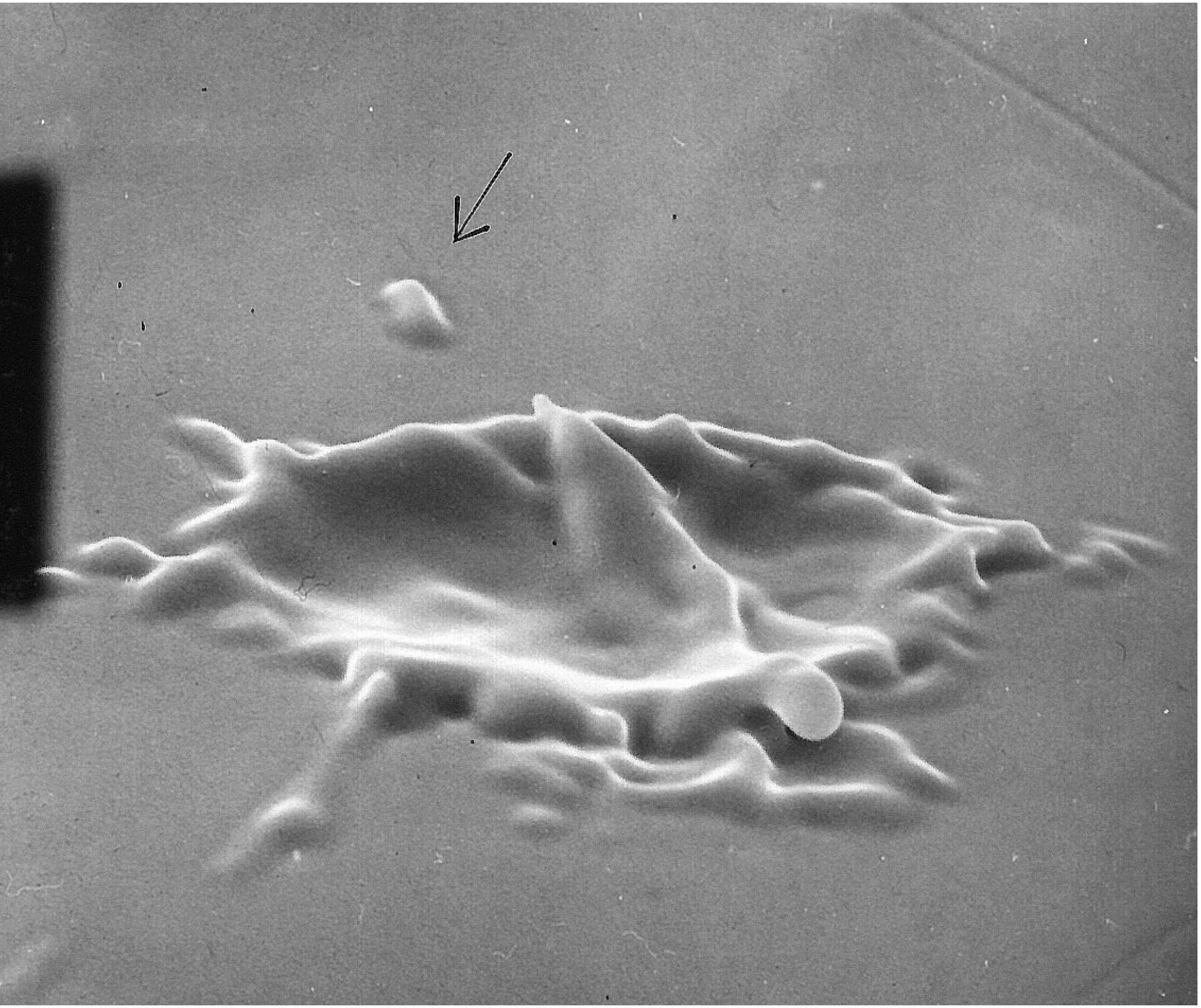


Computer control & power supplies

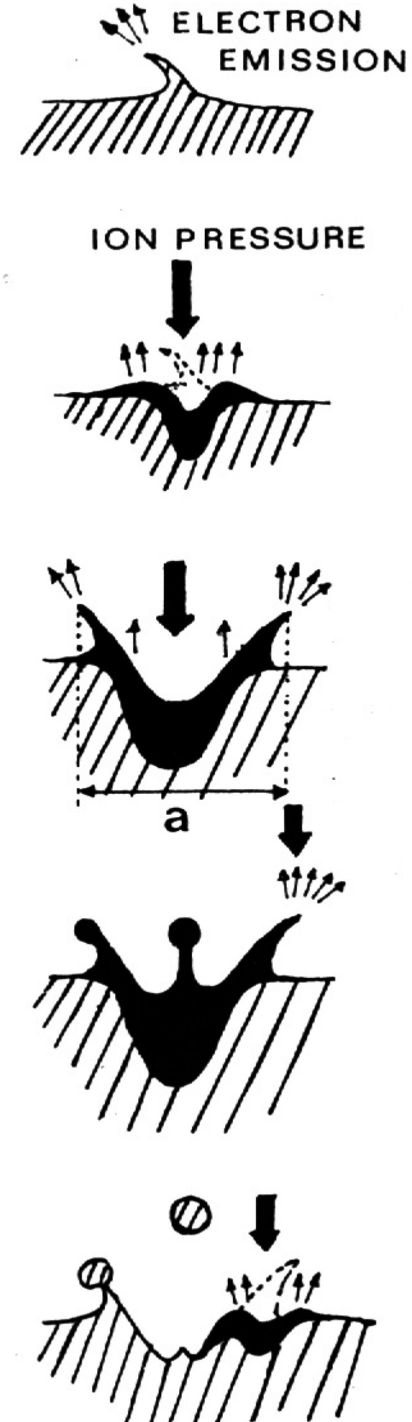
Turbo pumps

Photo courtesy of Joerg Vetter, Metaplas

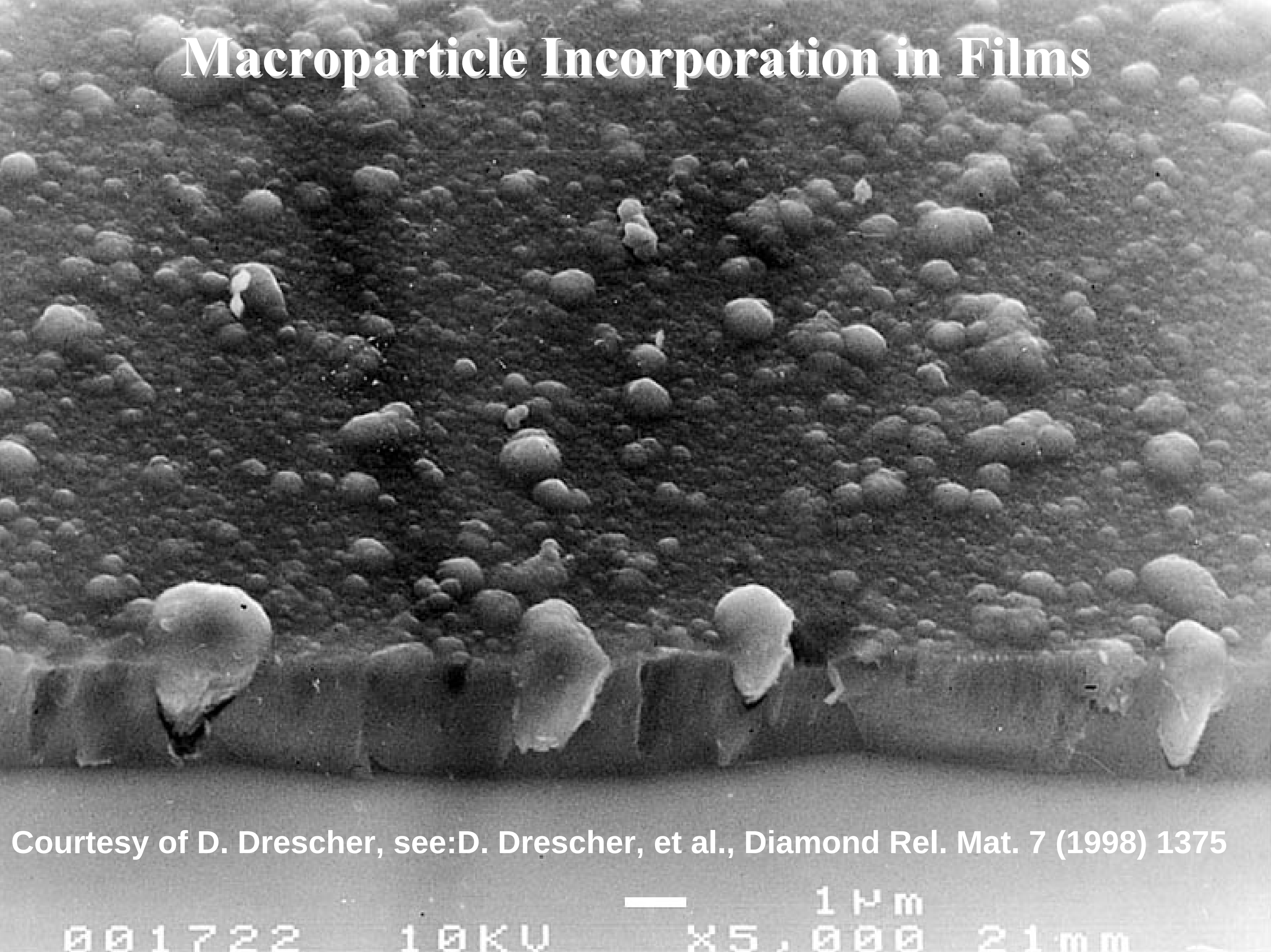
Macroparticle Generation



10 ns, Mo, Figure courtesy of B. Jüttner

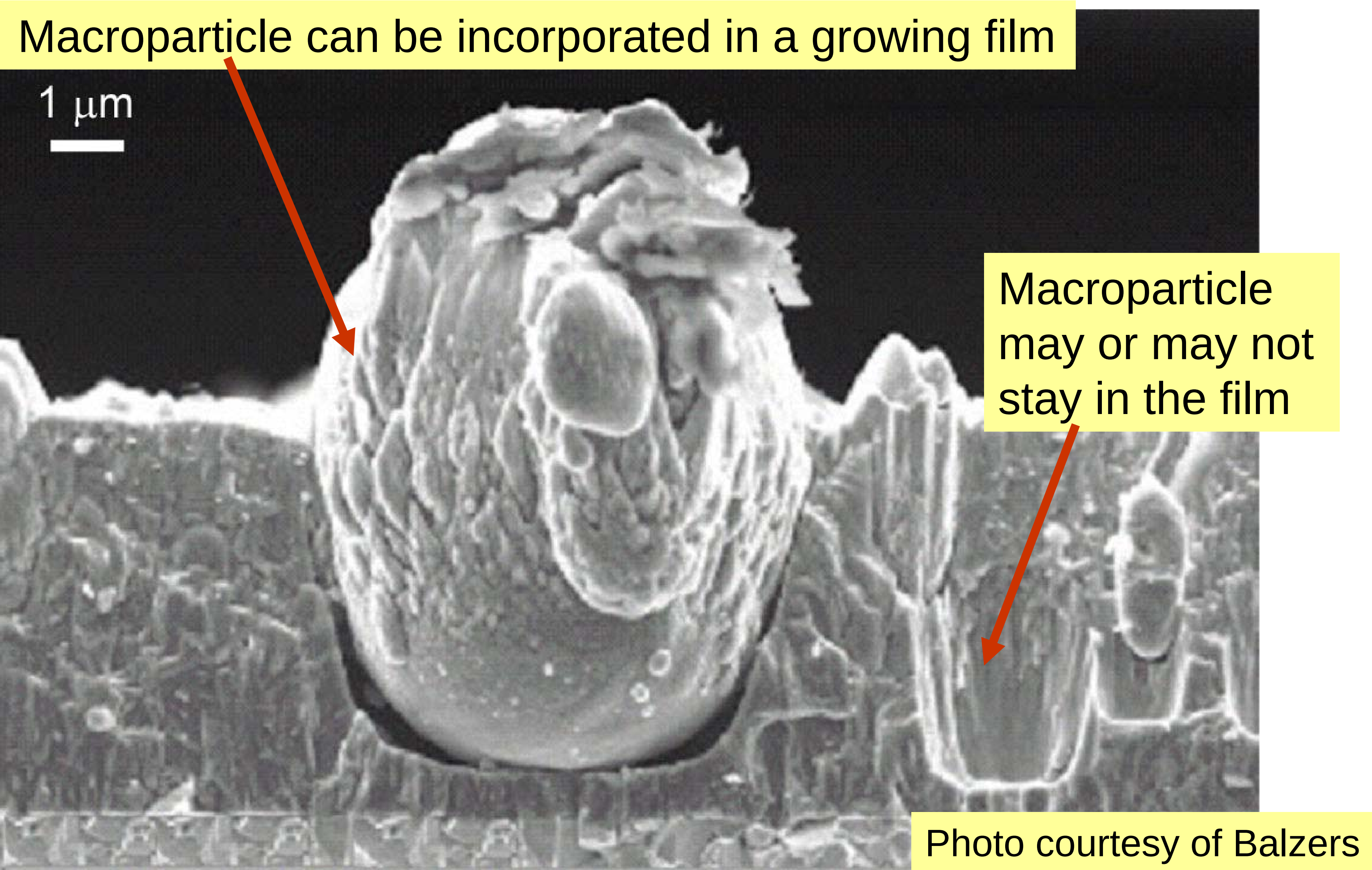


Macroparticle Incorporation in Films



Courtesy of D. Drescher, see:D. Drescher, et al., Diamond Rel. Mat. 7 (1998) 1375

Defect Formation by Incorporation of Macroparticles



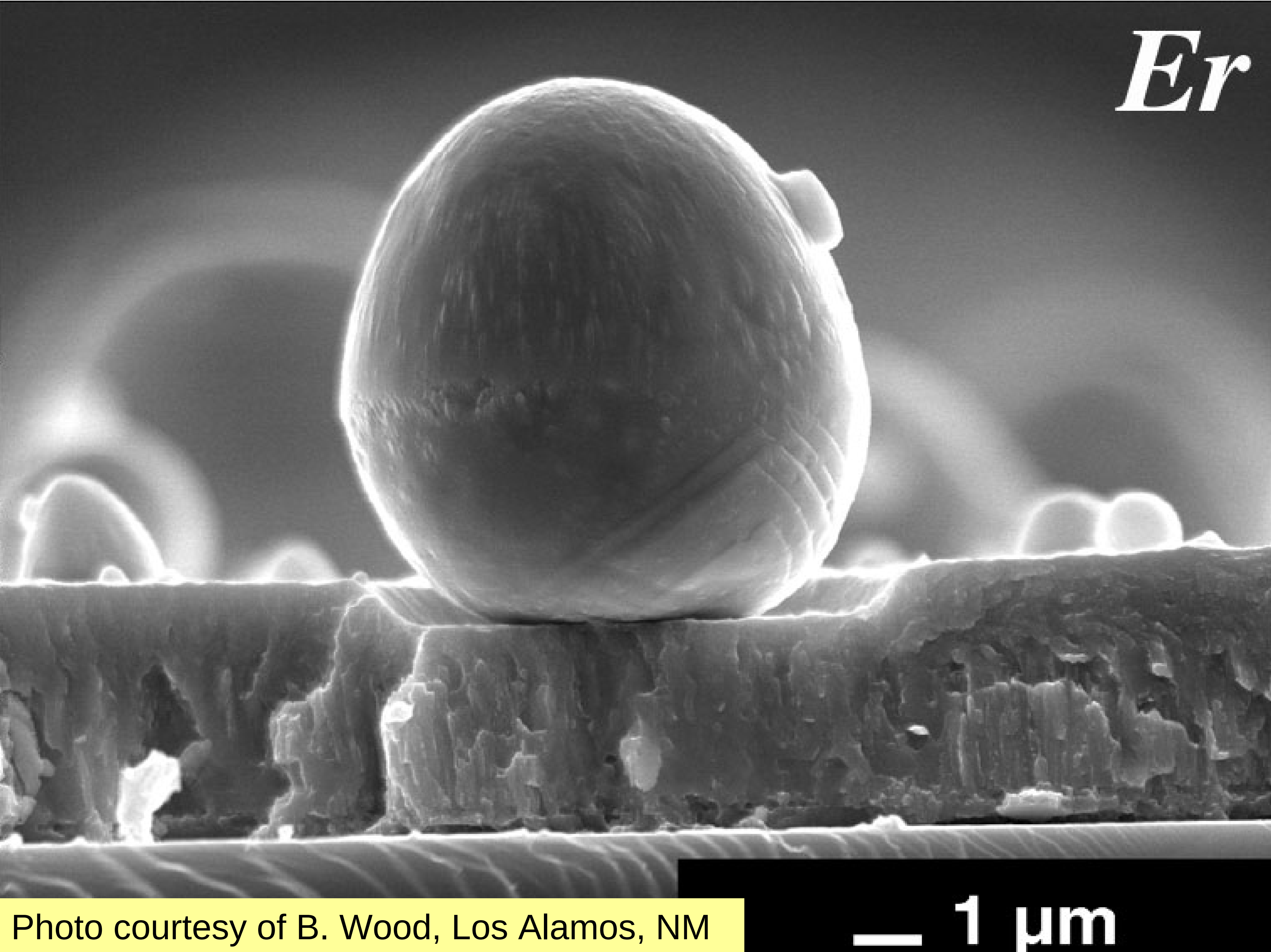
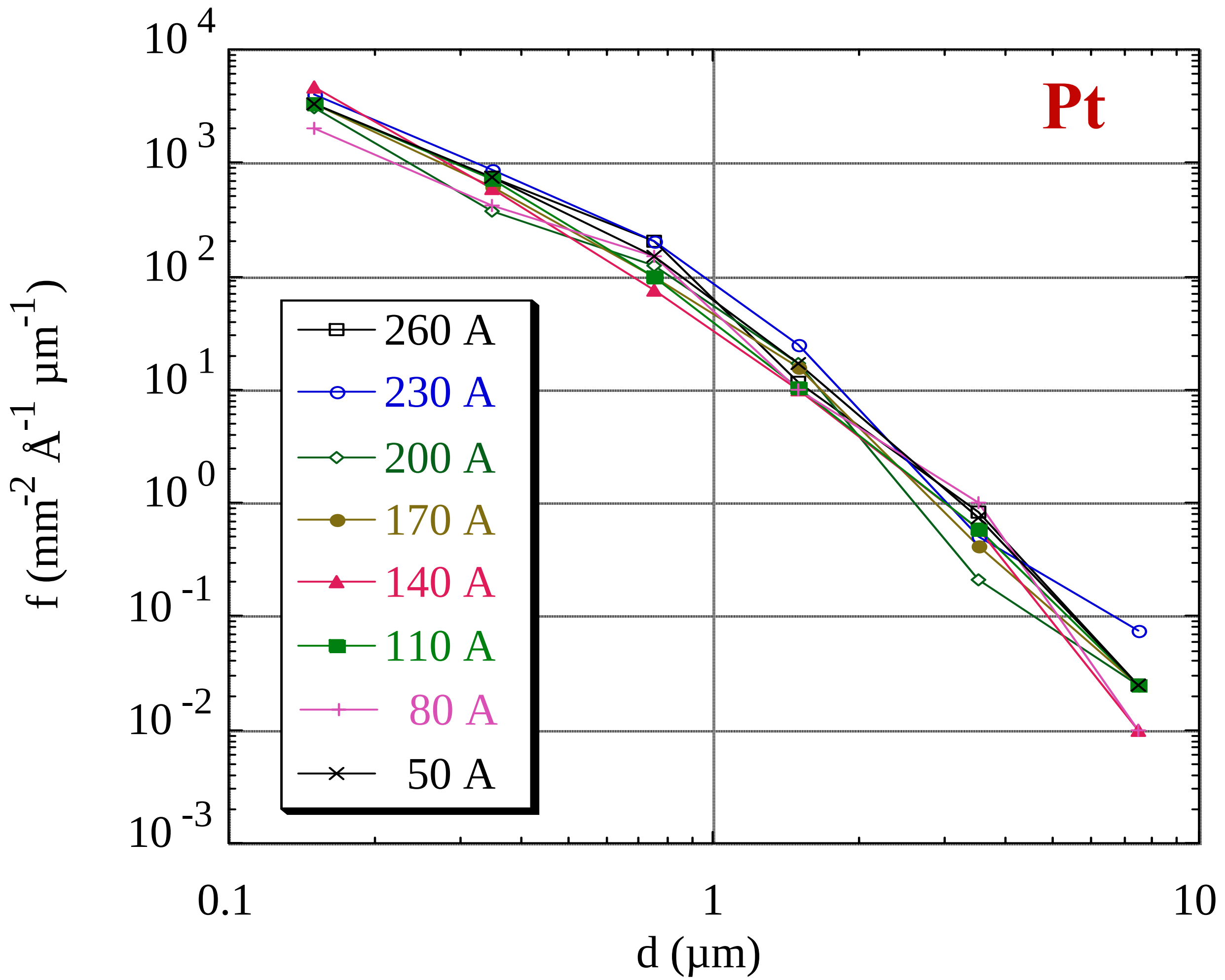


Photo courtesy of B. Wood, Los Alamos, NM

Macroparticle Distribution

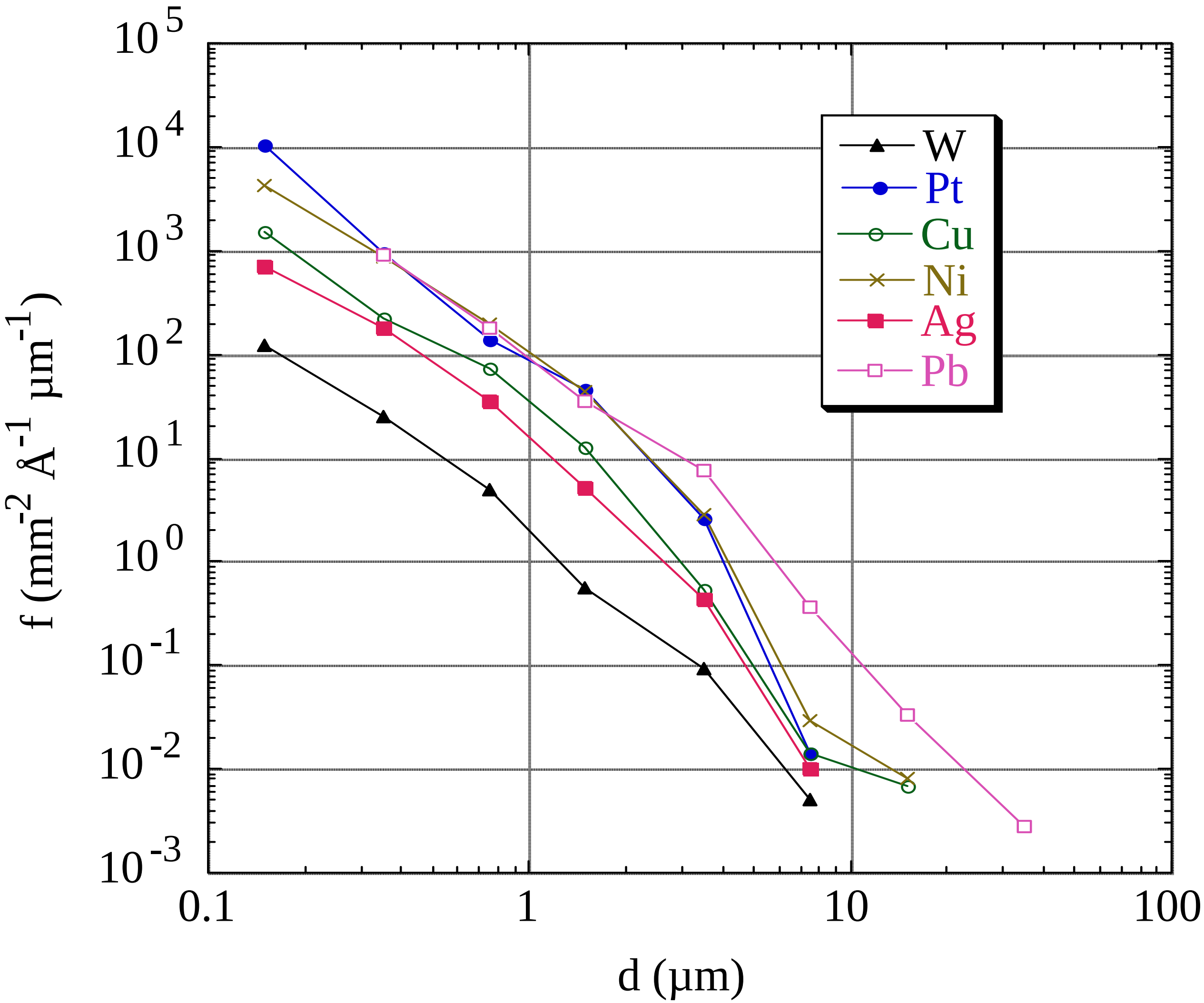
- Macroparticle generation does not depend on arc current:



Anders, *IEEE Trans. Plasma Sci.* **21** (1993) 440

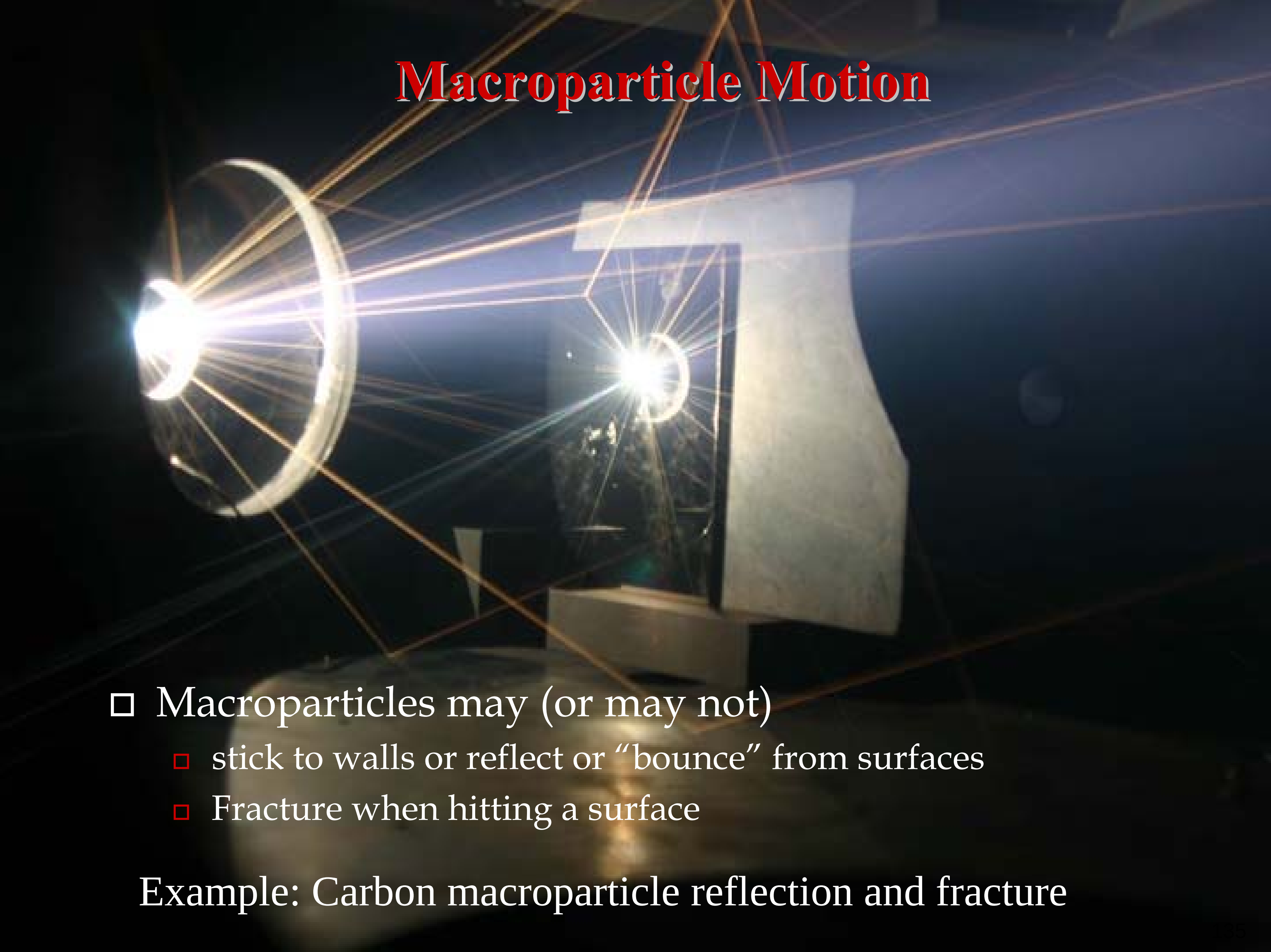
Macroparticle Distribution

- Materials of lower melting point have larger macroparticles
- Lower end of distribution is determined by instrumentation



Anders, IEEE Trans. Plasma Sci. **21** (1993) 440

Macroparticle Motion

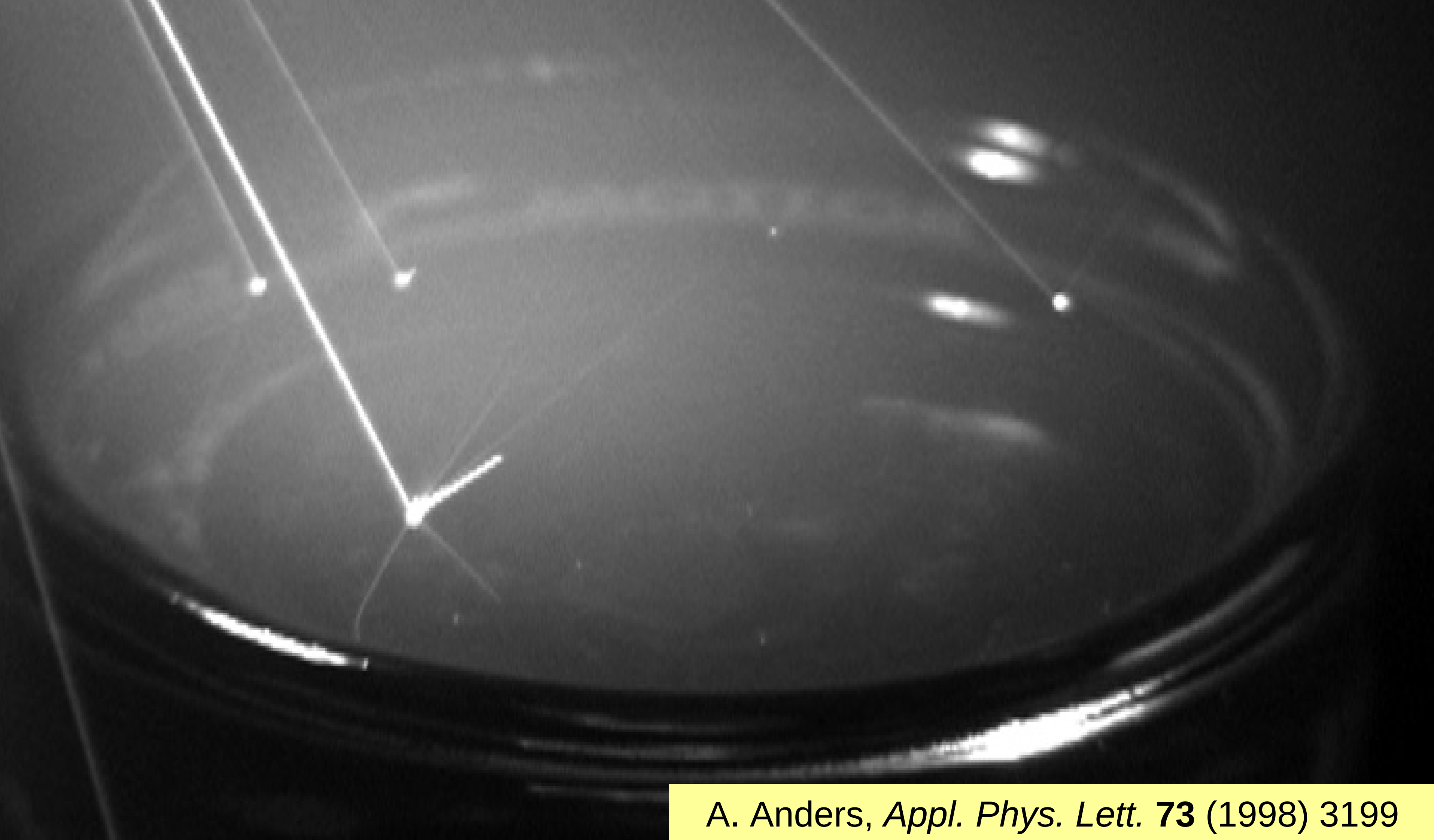


- Macroparticles may (or may not)
  - stick to walls or reflect or “bounce” from surfaces
  - Fracture when hitting a surface

Example: Carbon macroparticle reflection and fracture

Macroparticle Motion

- Macroparticle reflect even from a liquid (!) surface in vacuum (liquid was vacuum pump oil)



A. Anders, *Appl. Phys. Lett.* **73** (1998) 3199

Macroparticle Removal by Magnetic Filtering

ELECTRONS

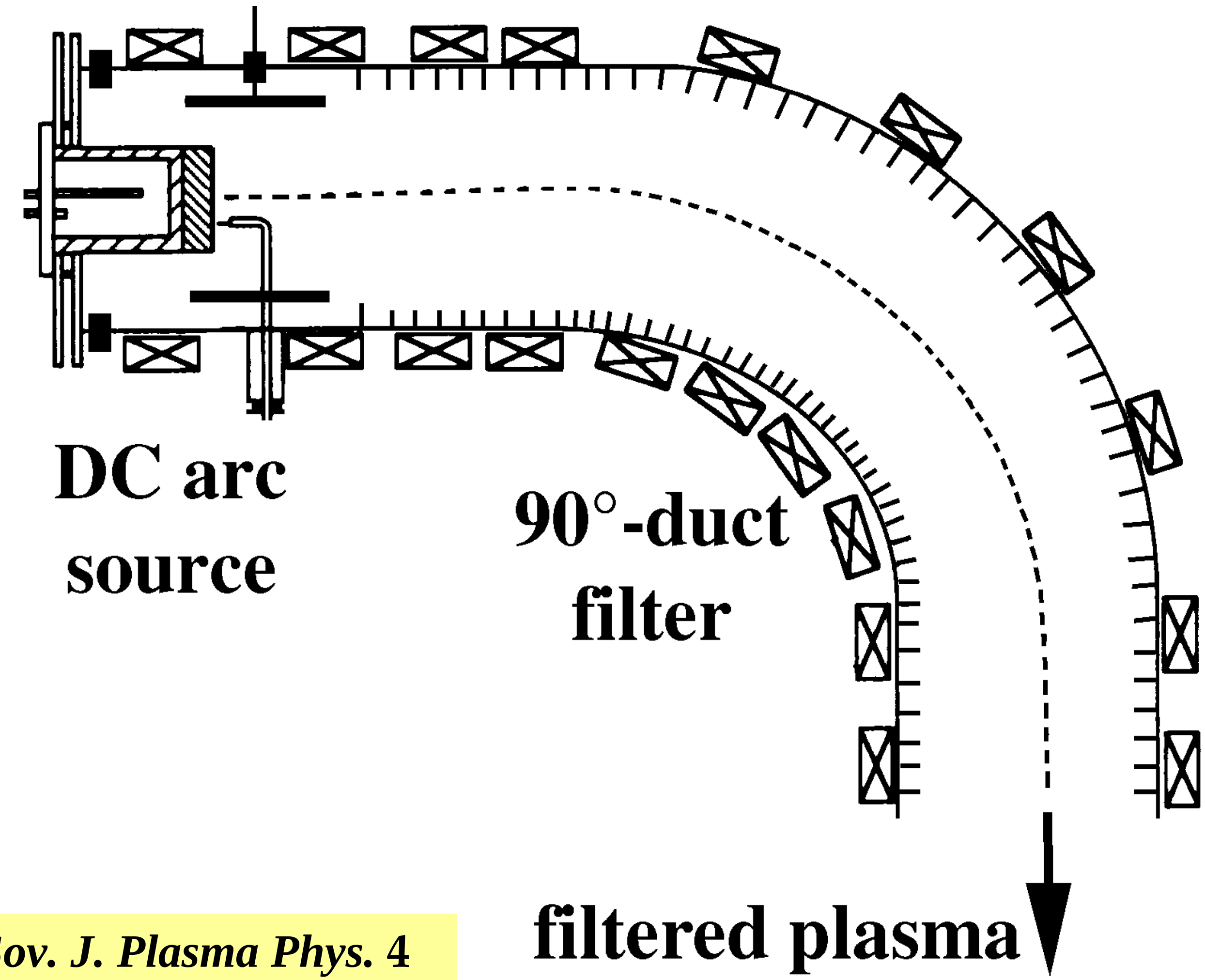
- ***Electrons are guided by magnetic field***: they gyrate around and along field lines
- Electron gyration radius
  $$r_{c,e} = \frac{v_\perp}{\omega_{c,e}} = \frac{m_e v_\perp}{e\,B}$$
- Electron motion perpendicular to field lines is facilitated by collisions; displacement is about one gyration radius

IONS

- Ions cannot be separated from electrons due to electric fields (plasma is quasi-neutral)
- ***Ions are guided by electric potential minimum*** along magnetic field lines

Transport of plasma in filters is a combined magnetic and electric mechanism

Classic 90° Duct



I.Aksenov et al., *Sov. J. Plasma Phys.* 4 (1978) 425-428

Out-of-plane, Double-bent Filter

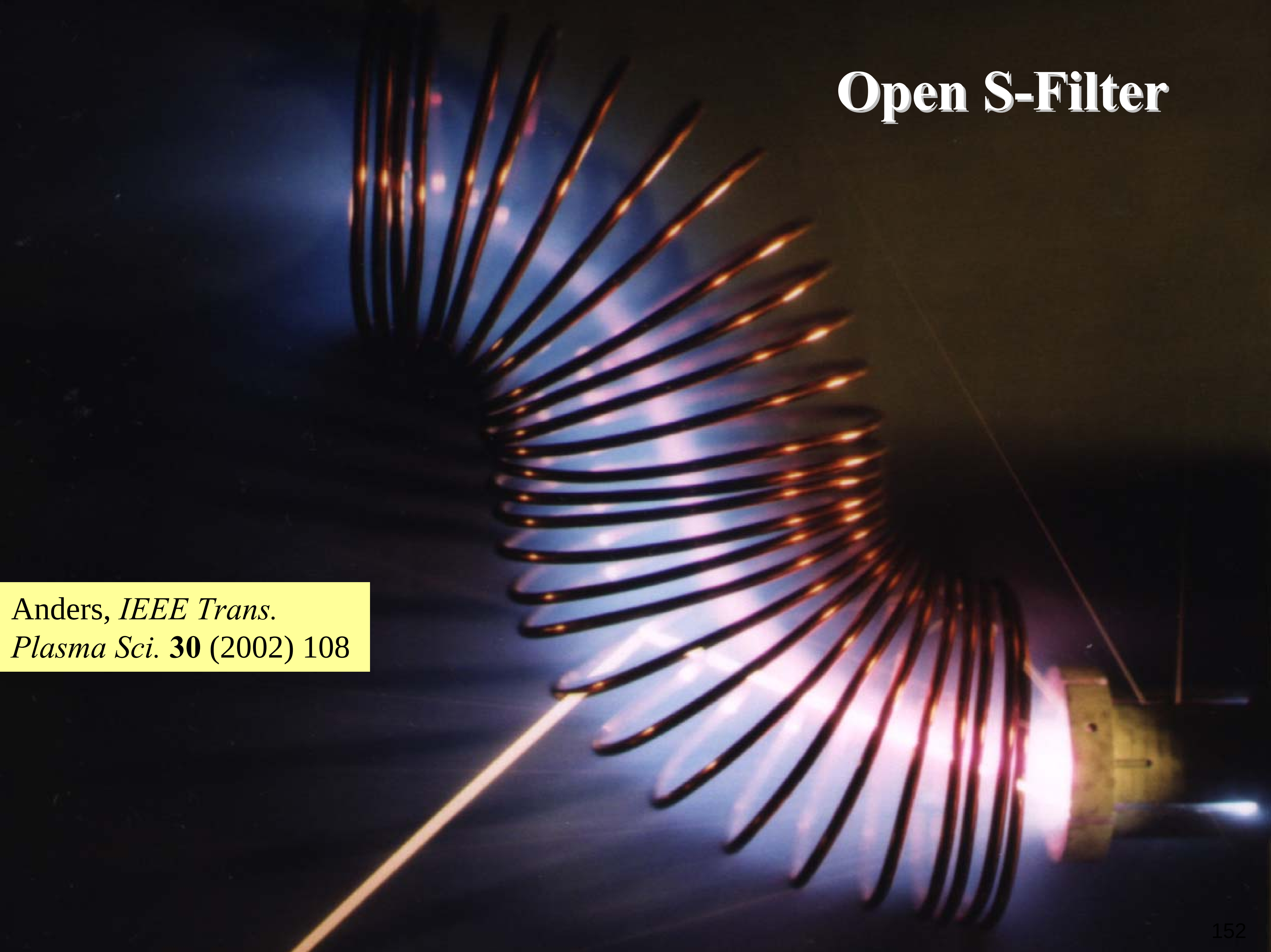
- Out-of-plane filter from Nanyang Technical University
- closed
- commercial version
- Shimadzu DLC-MR3CA

Open 90° Filter

- Open filter: e.g. freestanding 90° filter:
  - Openings allow macroparticles to leave the filter volume
  - High current required (e.g. arc current in series)

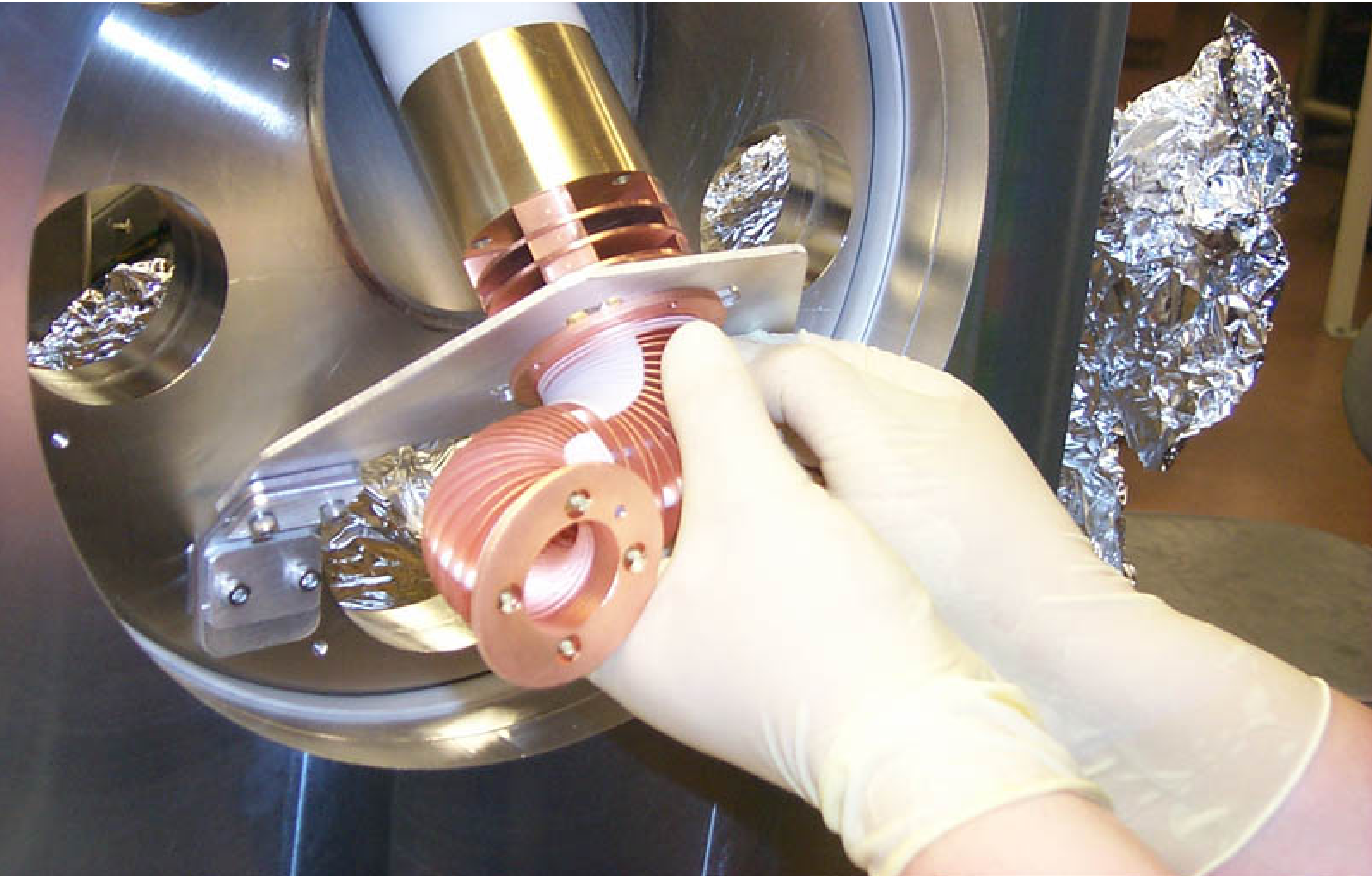
review on filters: A. Anders, *Surf. Coat. Technol*. **120-121** (1999) 319

Open S-Filter



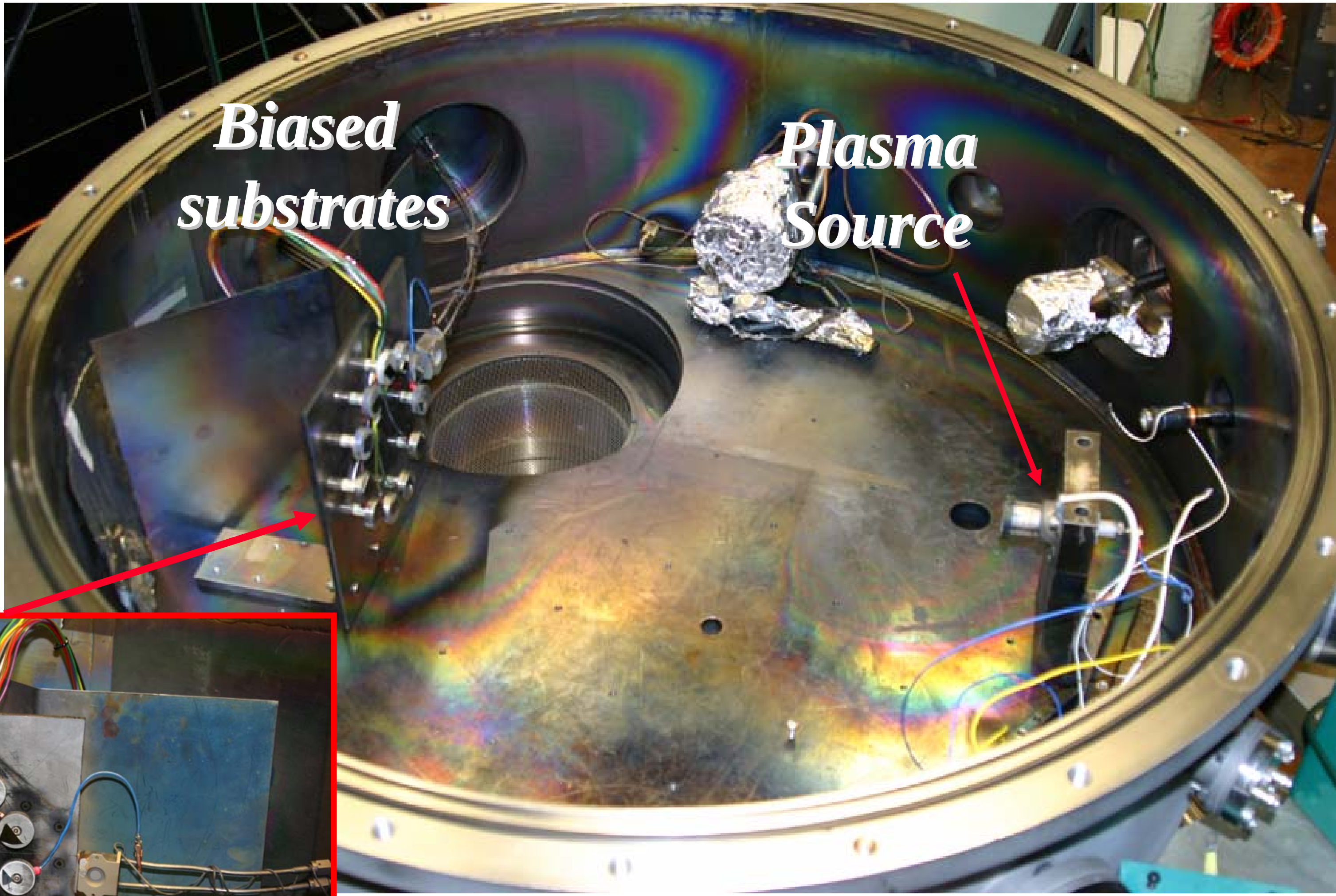
Anders, *IEEE Trans. Plasma Sci.* **30** (2002) 108

"Twist Filter": Open, Twisted S-Filter



Energetic Condensation

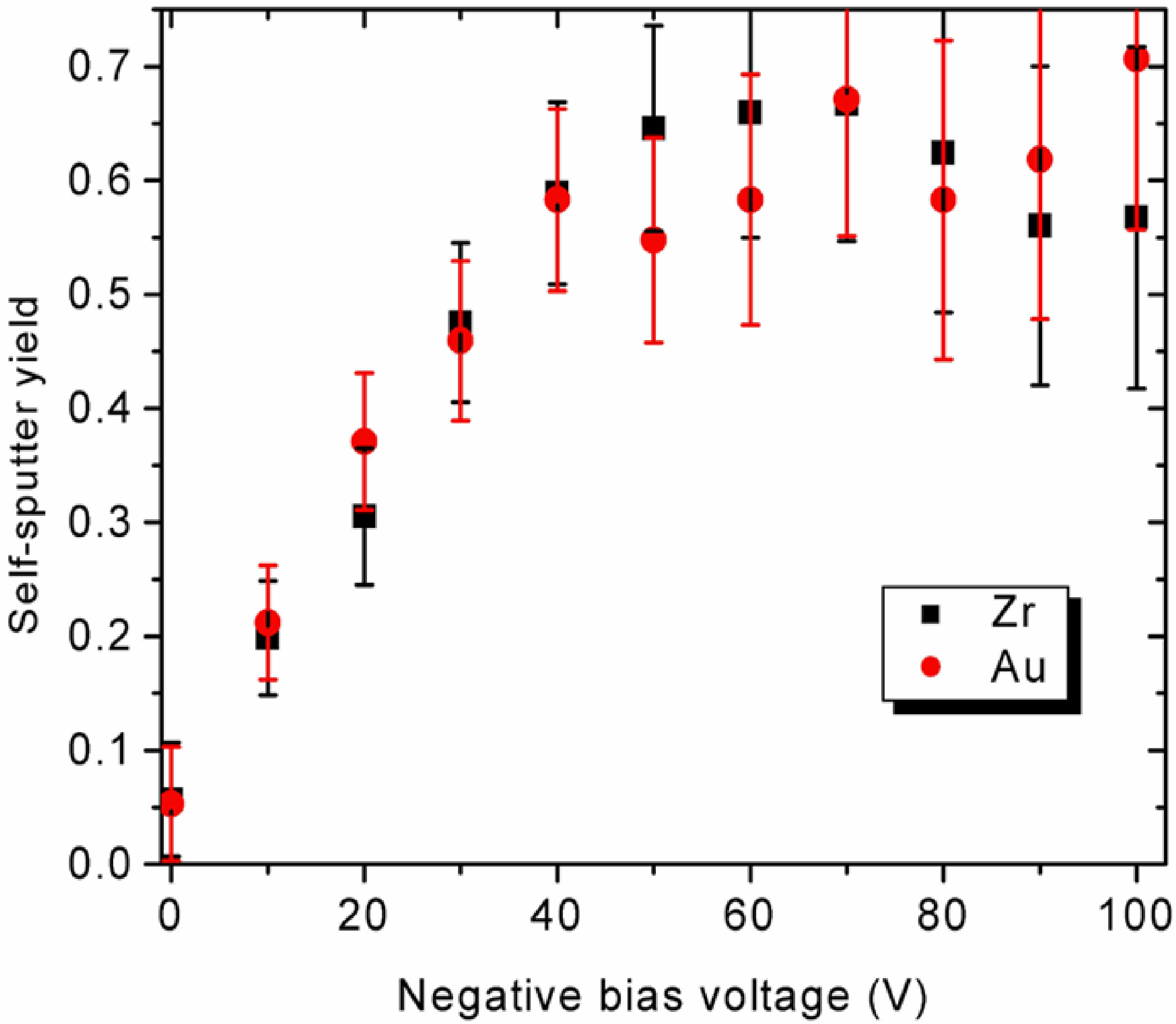
Bias-(Energy!)-dependent Condensation



A. Anders, *Appl. Phys. Lett.*, **85** (2004) 6137

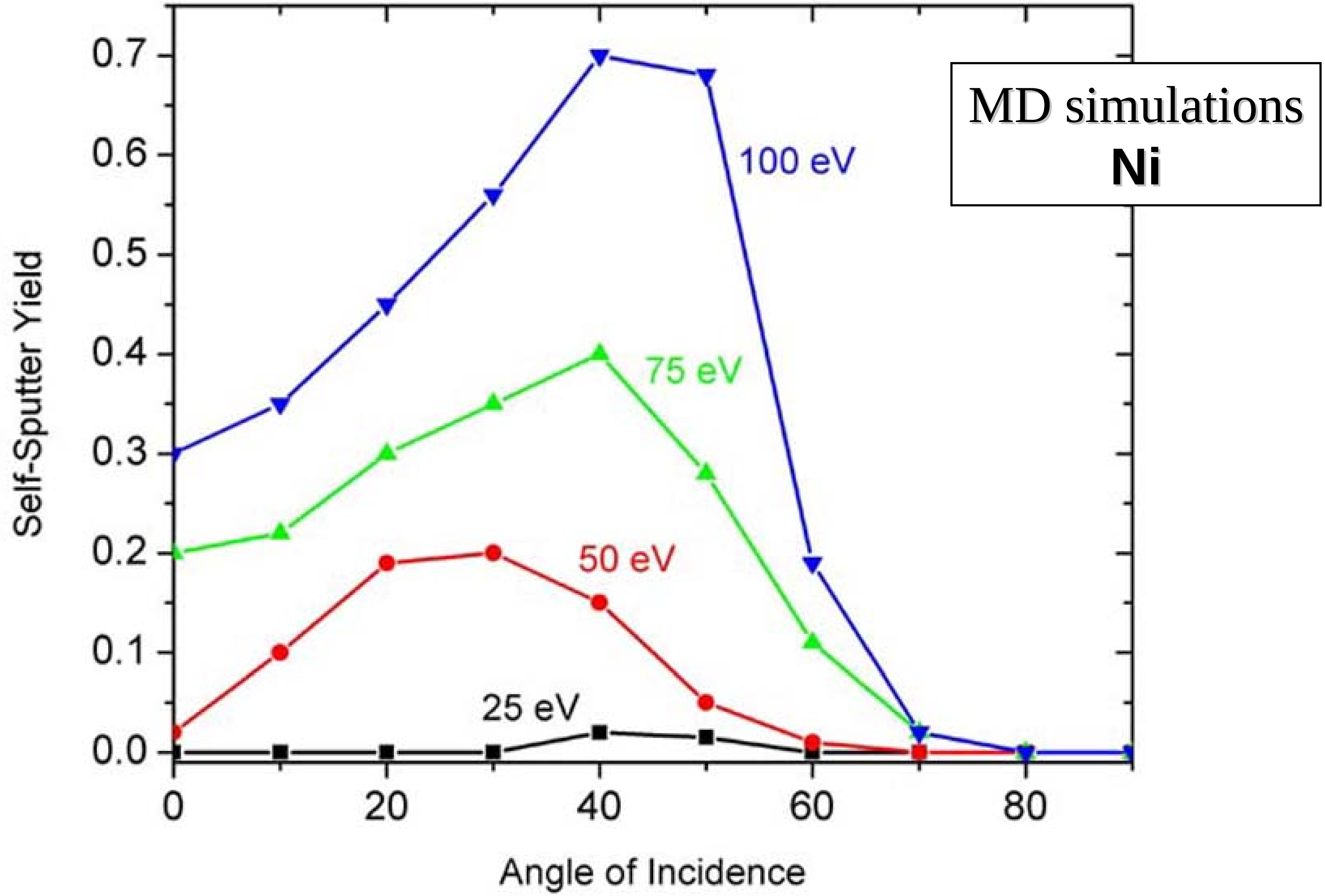
Bias-(Energy!)-dependent Condensation

- Result: at even moderate bias, film formation is reduced by self-sputtering
- Extreme examples: Au, Zr



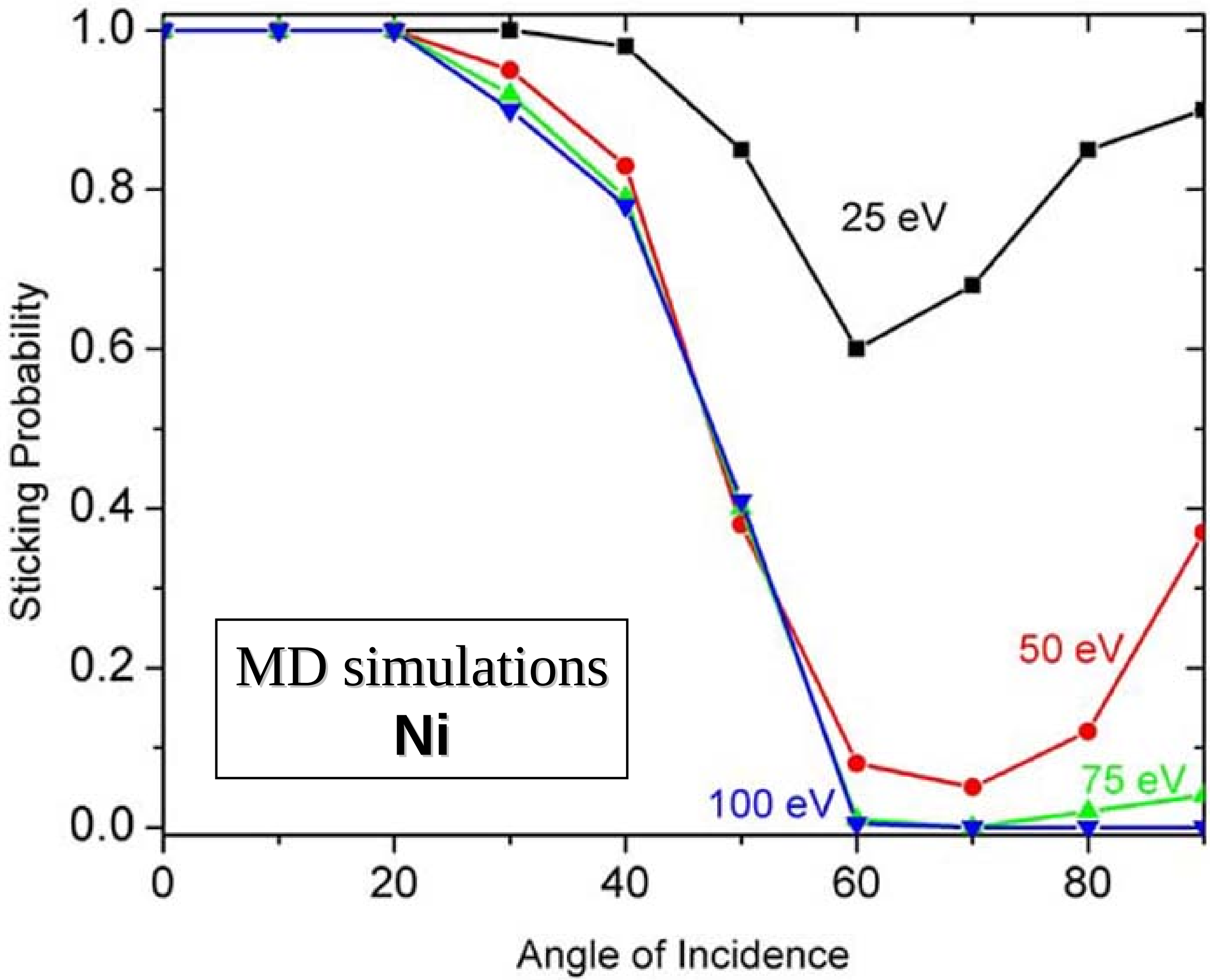
A. Anders, *Appl. Phys. Lett.*, **85** (2004) 6137

Self-Sputtering



Hanson et al., *J. Vac. Sci. Technol. A* **19** (2001) 820-825.

Sticking Probability



Hanson et al., *J. Vac. Sci. Technol. A* **19** (2001) 820-825.

Energetic Relation Between Implantation and Deposition Processes

Ion Energy

Implantation

Film growth is still possible for low duty cycle of bias

sputter yield = 1 for E_i=300-1200 eV

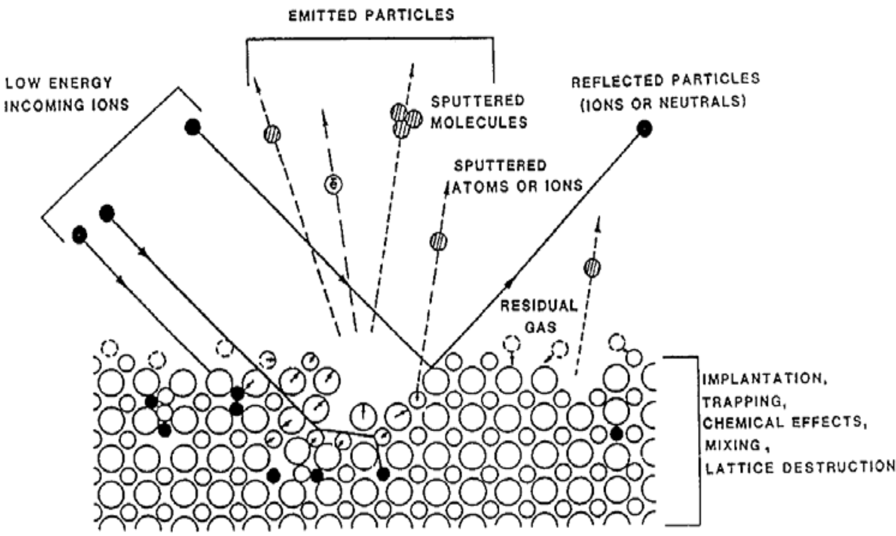
Subplantation

Deposition

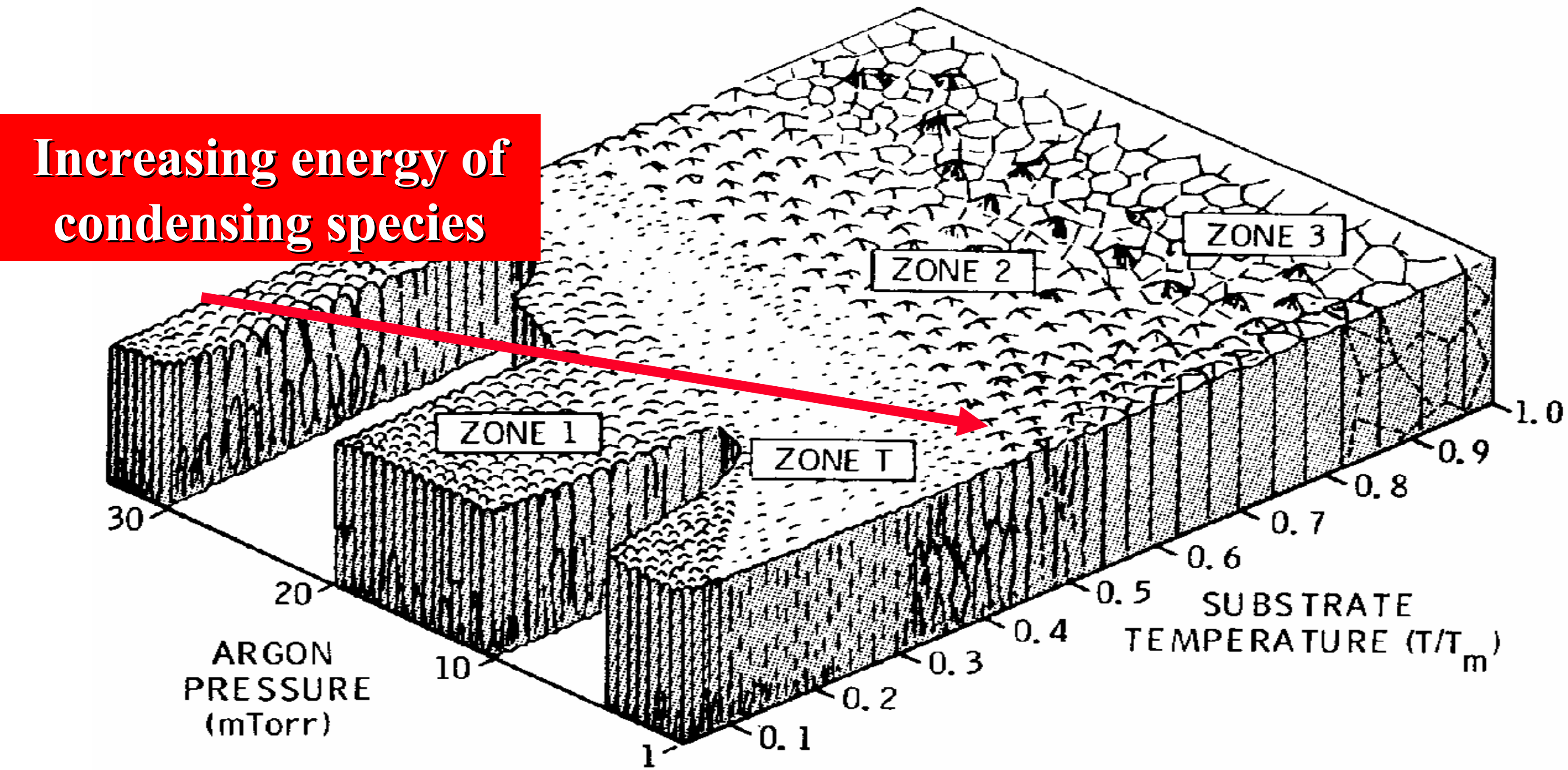
Ion plating, MePIIID	> 100 eV
cathodic arc deposition	~10-100 eV
sputtering	~1-10 eV
evaporation	~0.1 eV

Plasma Deposition: Surface Processes Affected by Energy of Incoming Ions

- Sticking / reflection
- Sputtering
- Secondary electron emission
- Subplantation / implantation
- Surface diffusion
- Defect generation
- Phase changes, including precipitation
- heating
- adsorption/desorption of gas
- reaction with background gas atoms



Structure Zone Diagram for Sputtered Films



Structure-zone diagram showing schematic microstructures of films deposited by cylindrical magnetron sputtering as a function of growth temperature and Ar pressure.

Thornton, J.Vac. Sci. Technol. 11 (1974) 666

Example for non-energetic condensation: "Long-through-sputtering"

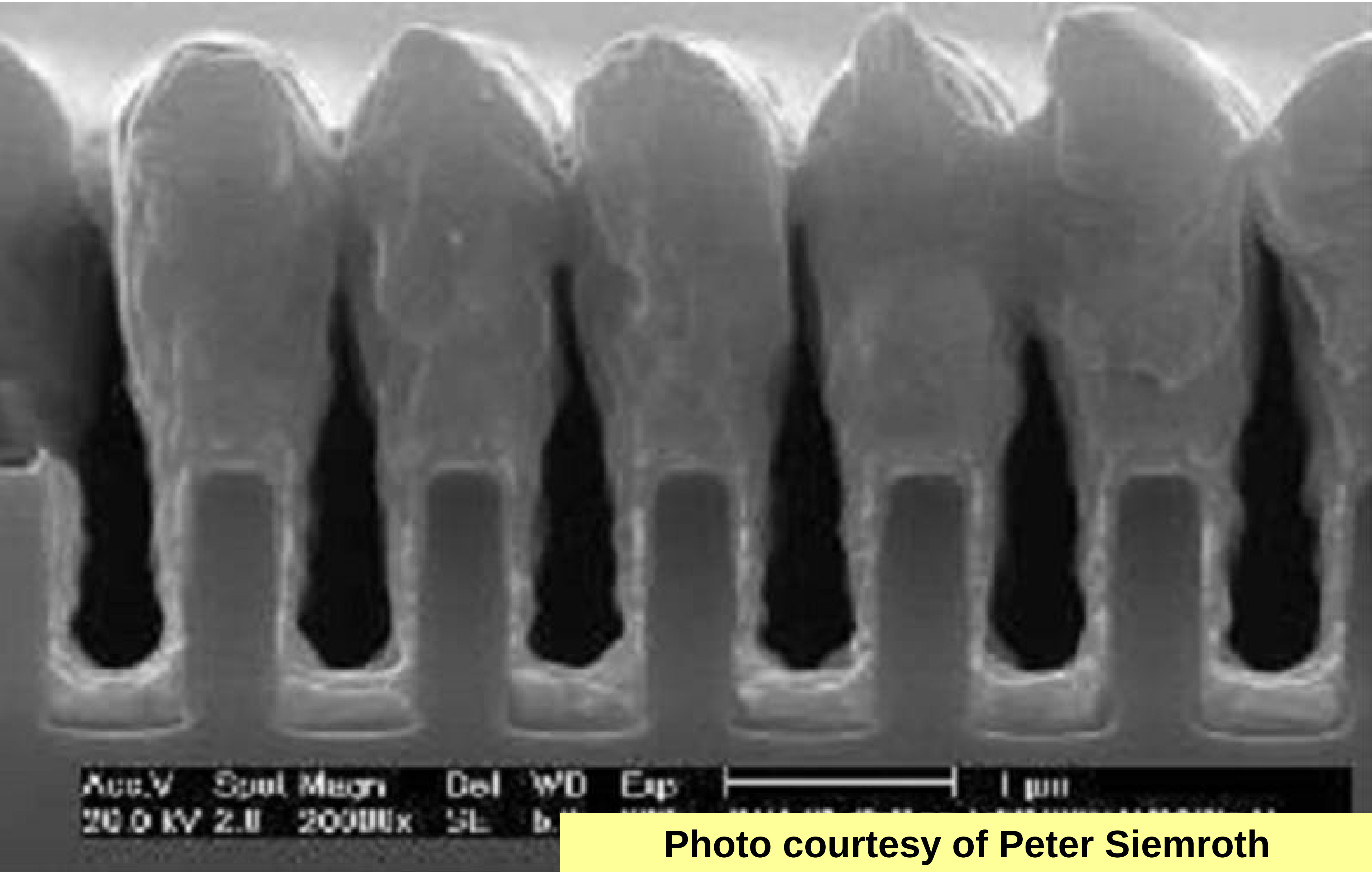
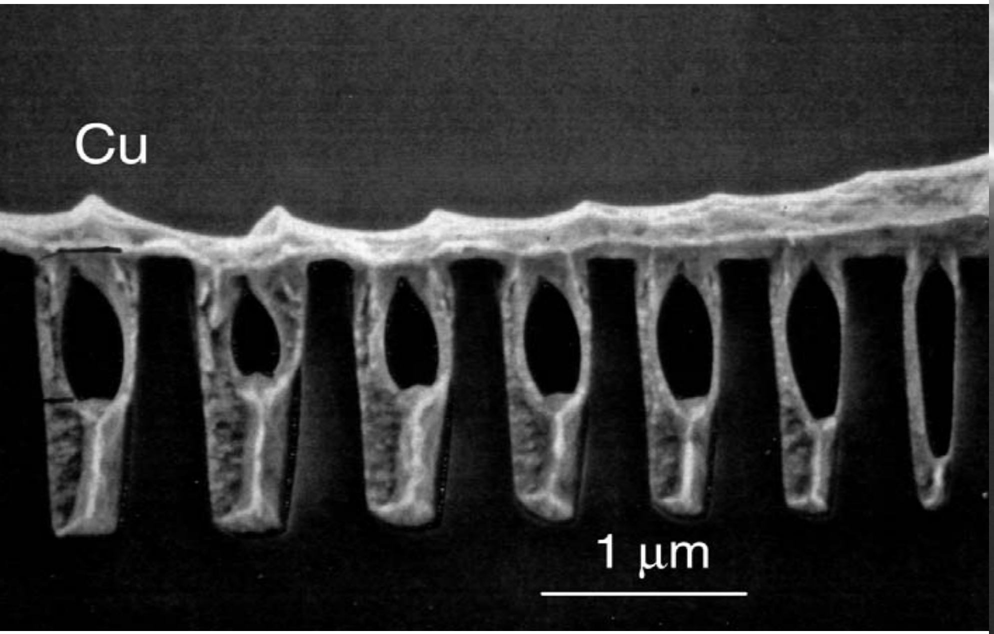
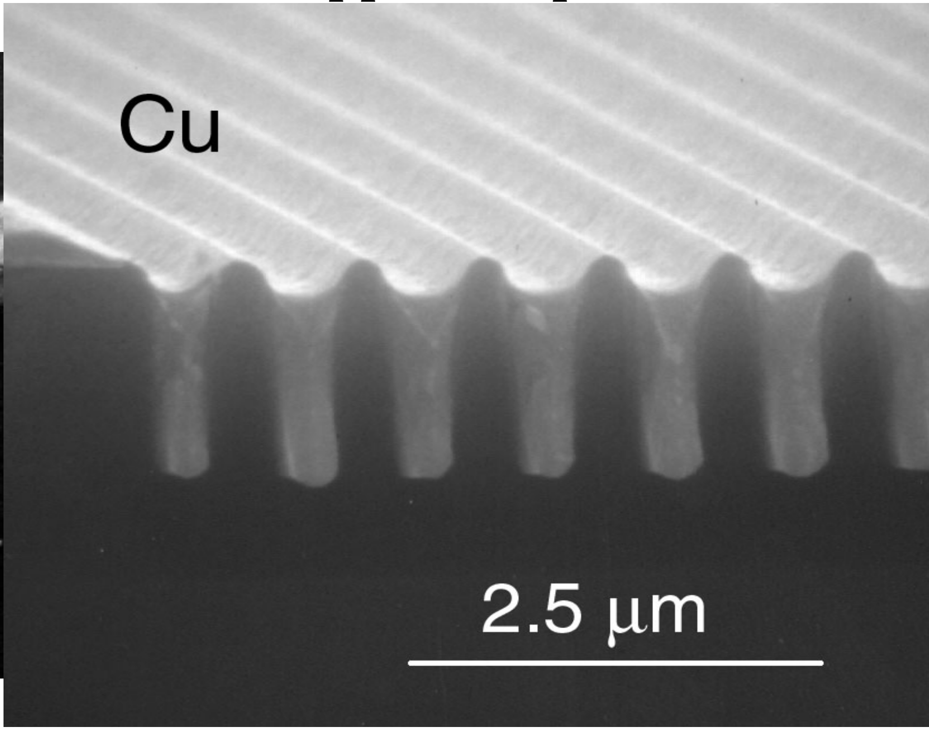


Photo courtesy of Peter Siemroth

Diffusion Barriers and Trench Filling

- Trench filling using MePIIID with filtered copper arc plasma





voids form if vapor / plasma does not have correct impact angle and energy

perfect filling of trenches, only possible by effects of limited sticking and self-sputtering under energetic conditions!

O.R. Monteiro, J. Vac. Sci. Technol. B **17** (1999) 1094

More Ta barrier films

Pulsed high-current filtered Arc; Fraunhofer Institute (IWS, Dresden)

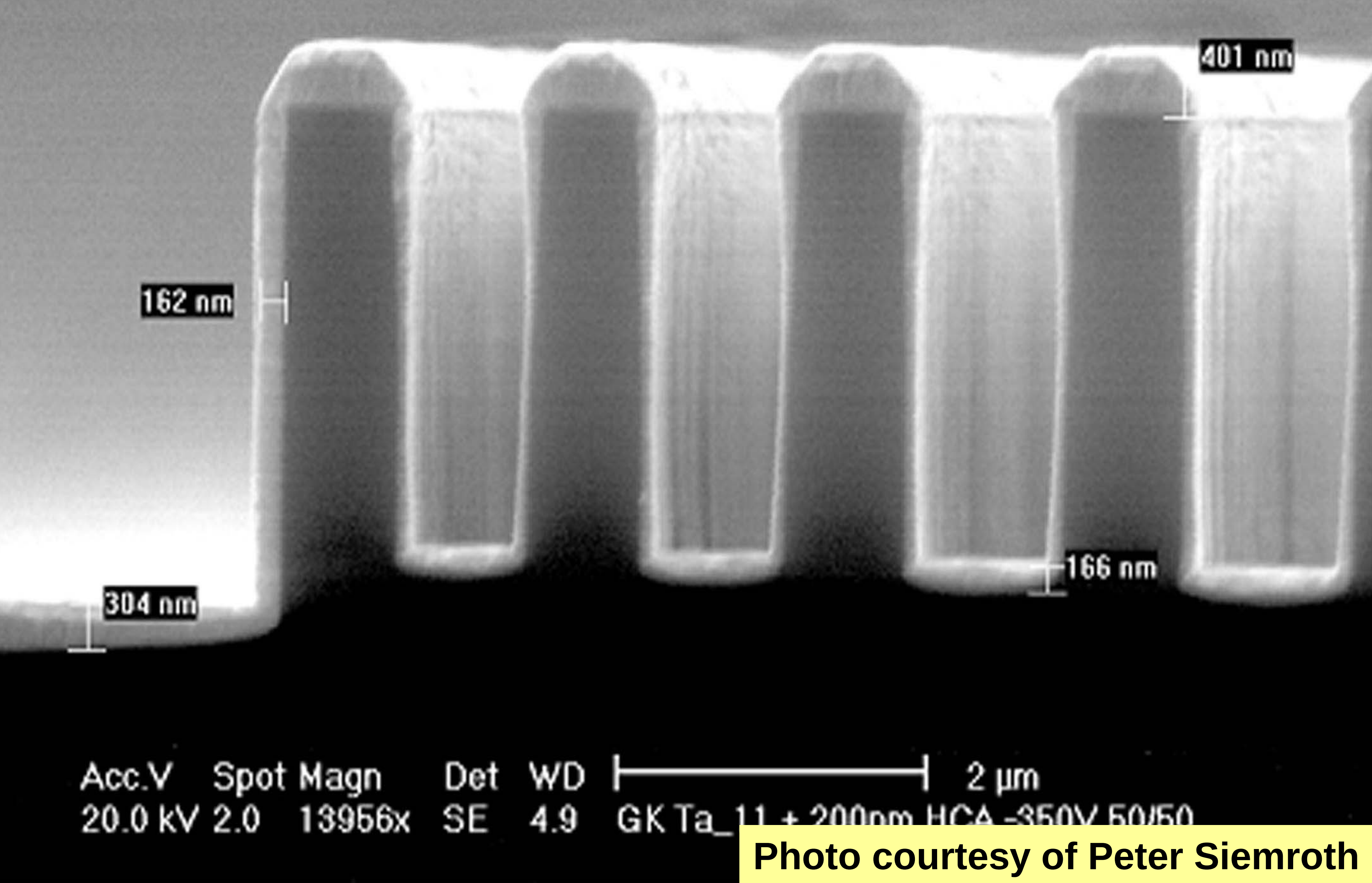
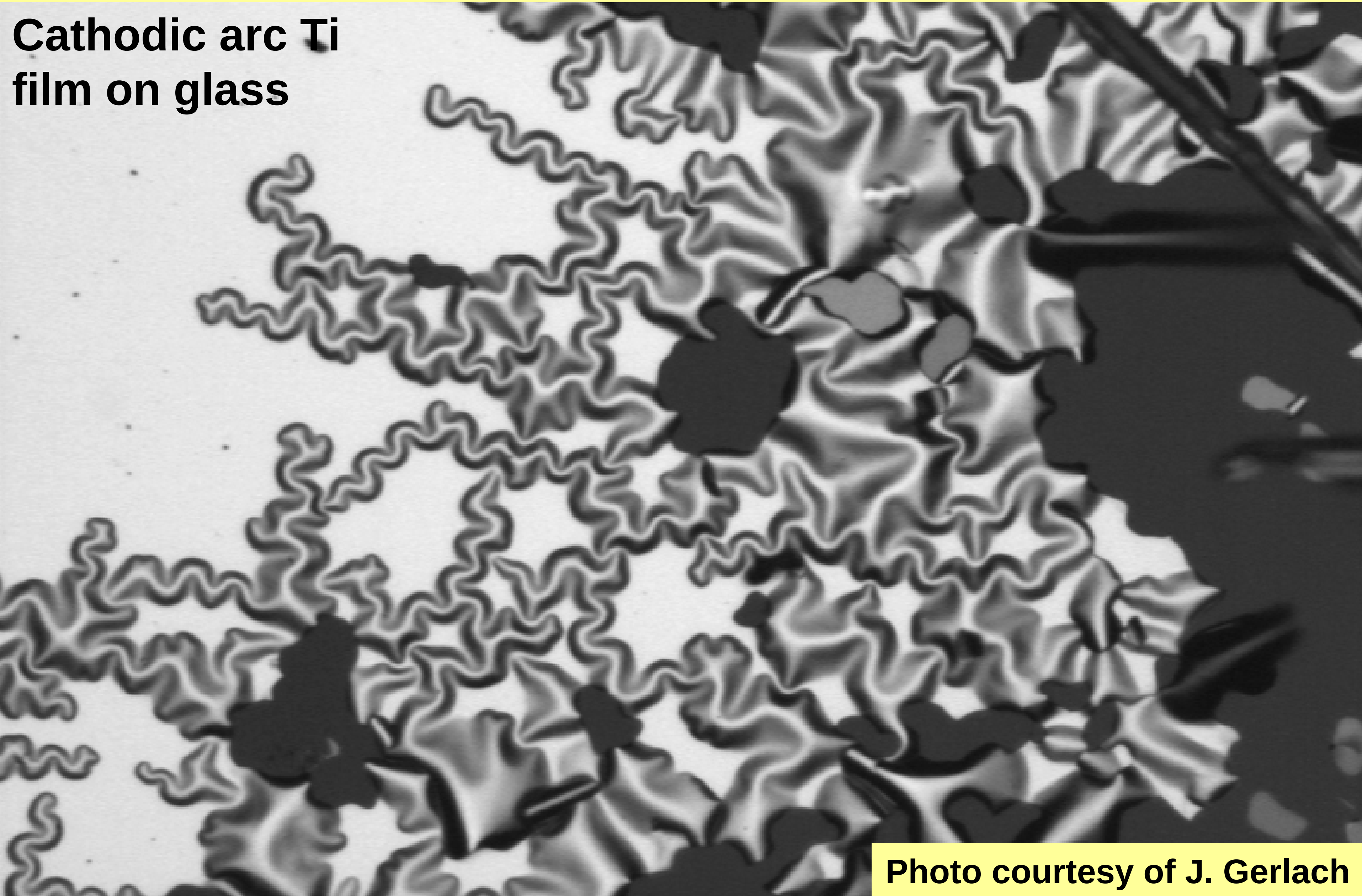


Photo courtesy of Peter Siemroth

Excessive Compressive Stress



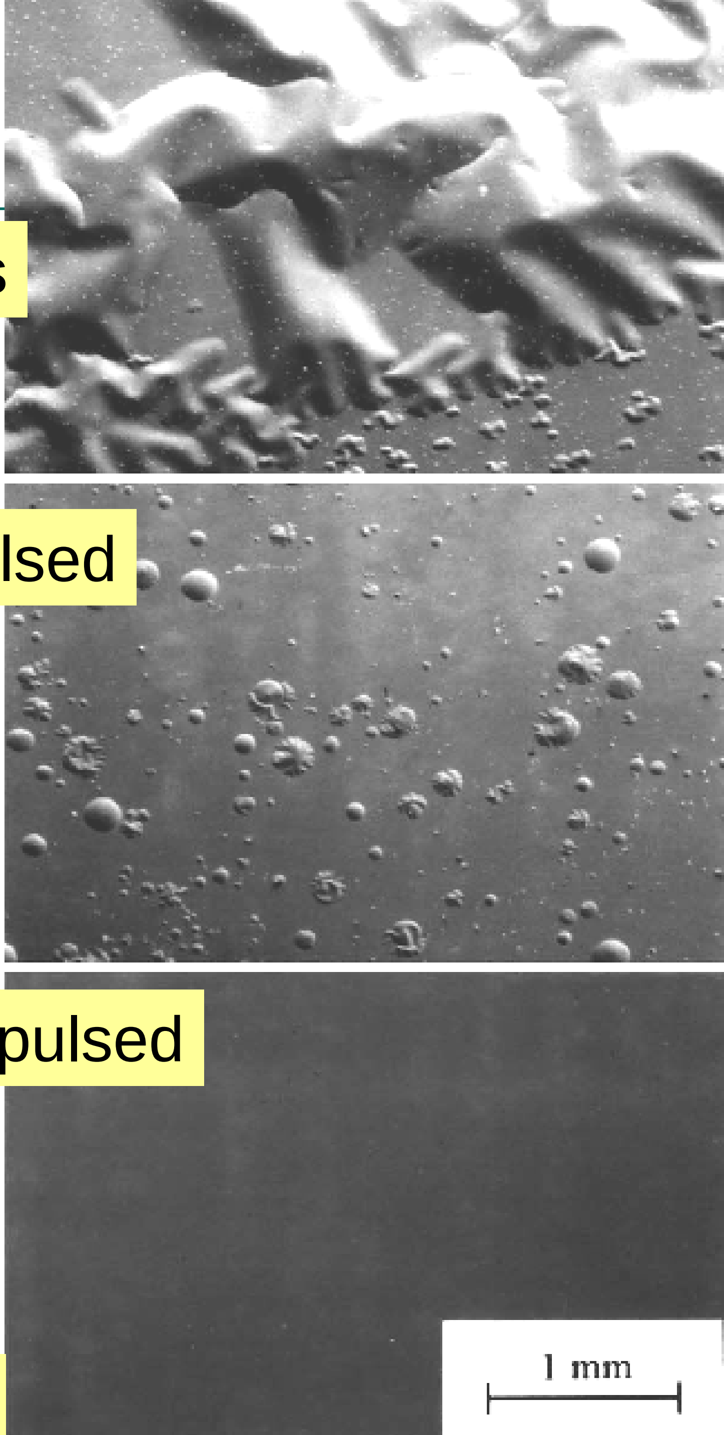
Improvement of Film Adhesion by Bias

Effect of ion energy on the adhesion of $Ag/YBa_2Cu_3O_x$ film on Si produced by MePIIID.

due to

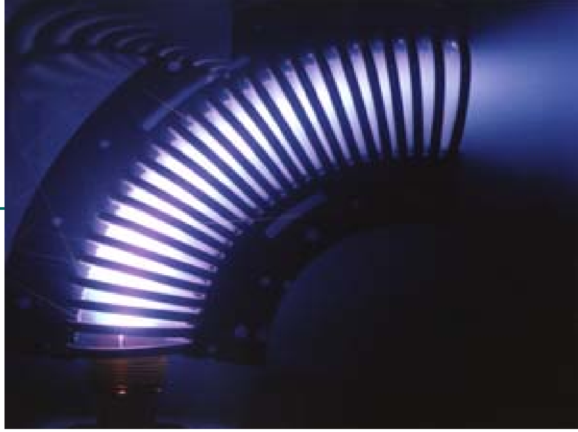
1. sputter removal of contaminants
2. ion mixing
3. stress relieve

Beautiful MD simulations by Australian group, see, e.g., M. Bilek, et al., *IEEE Trans. Plasma Sci.* **31** (2003) 939

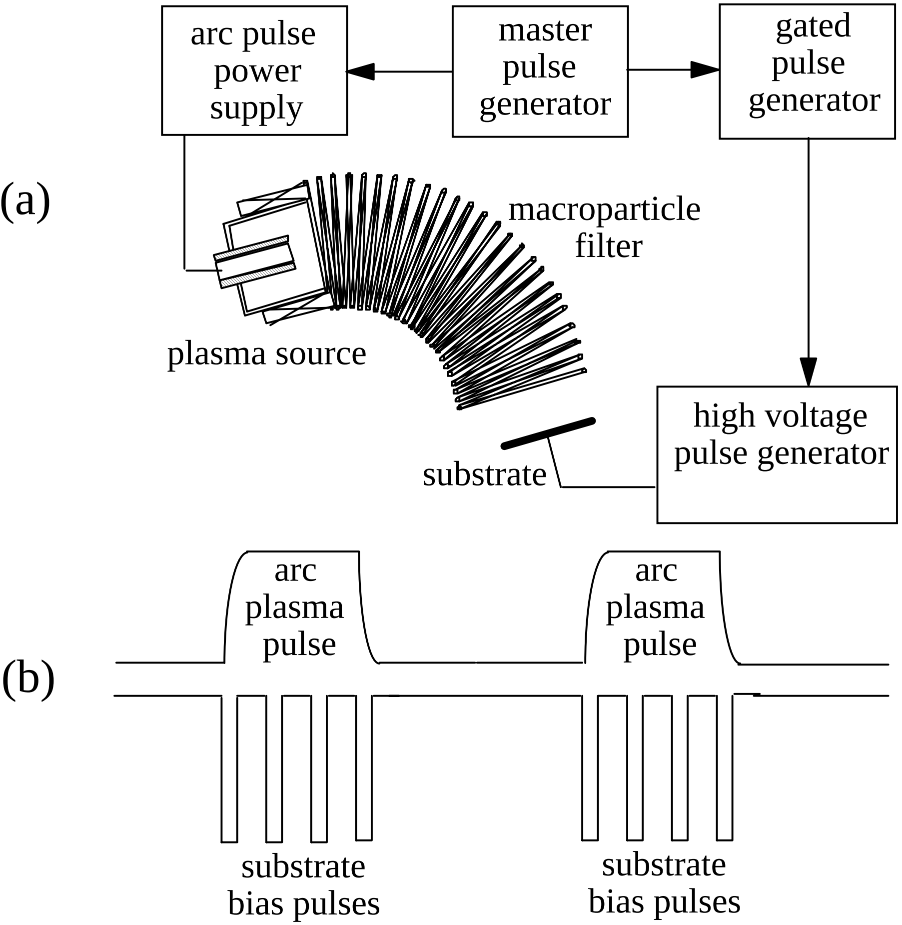


Anders, *J. Vac. Sci. Technol. B* **12** (**1994**) 815-820

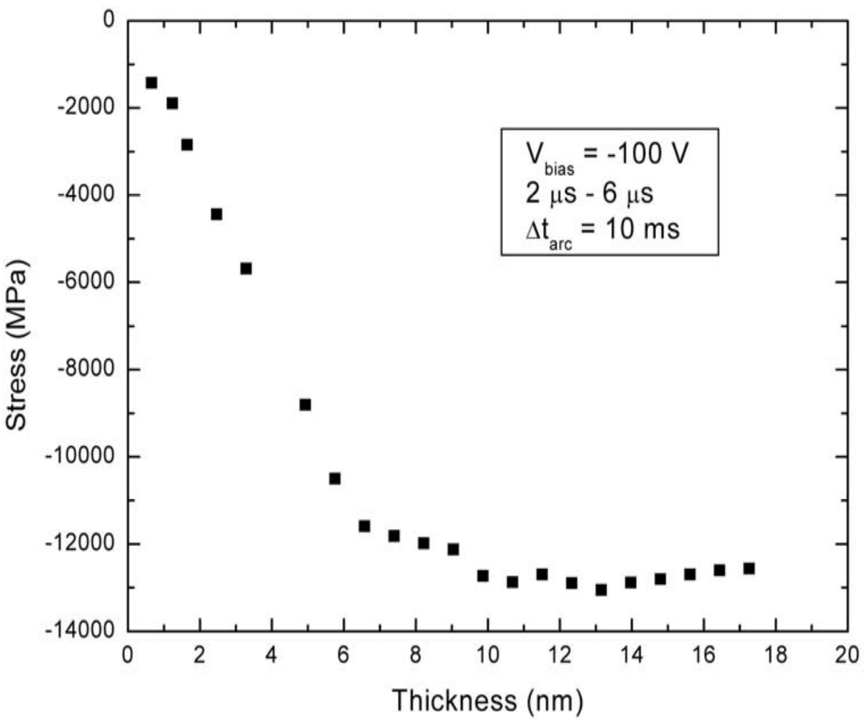
Buildup and Control of Intrinsic Stress in ta-C Films



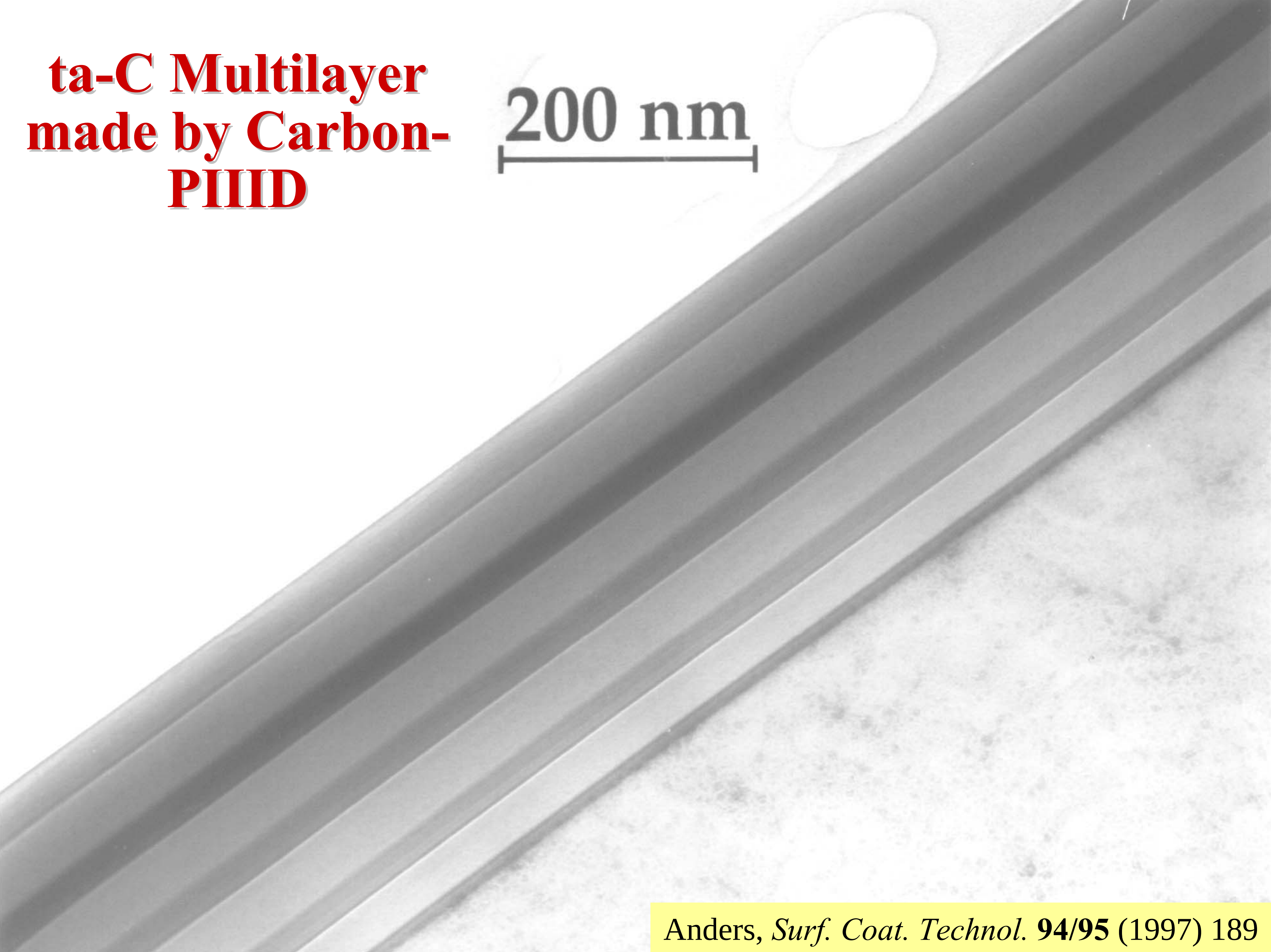
Filtered pulsed cathodic arc and pulsed bias



Pulsed bias voltage is used to change carbon energy and thereby bonding and stress in film



ta-C Multilayer made by Carbon-PIIID

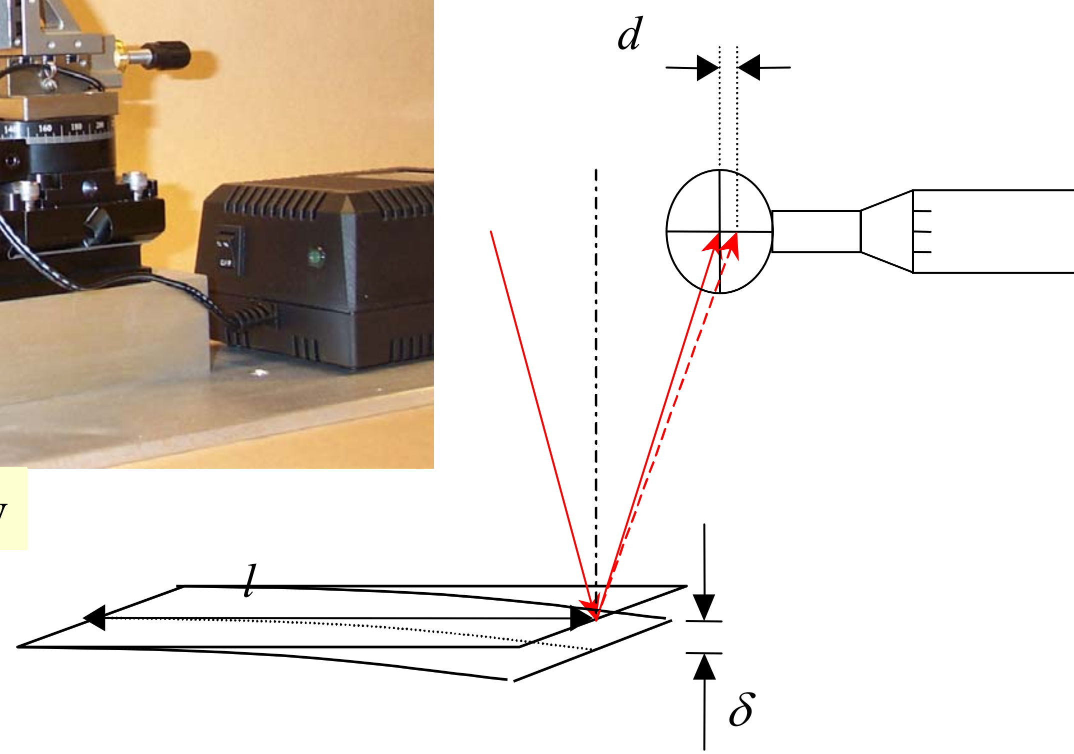


Anders, *Surf. Coat. Technol.* **94/95** (1997) 189

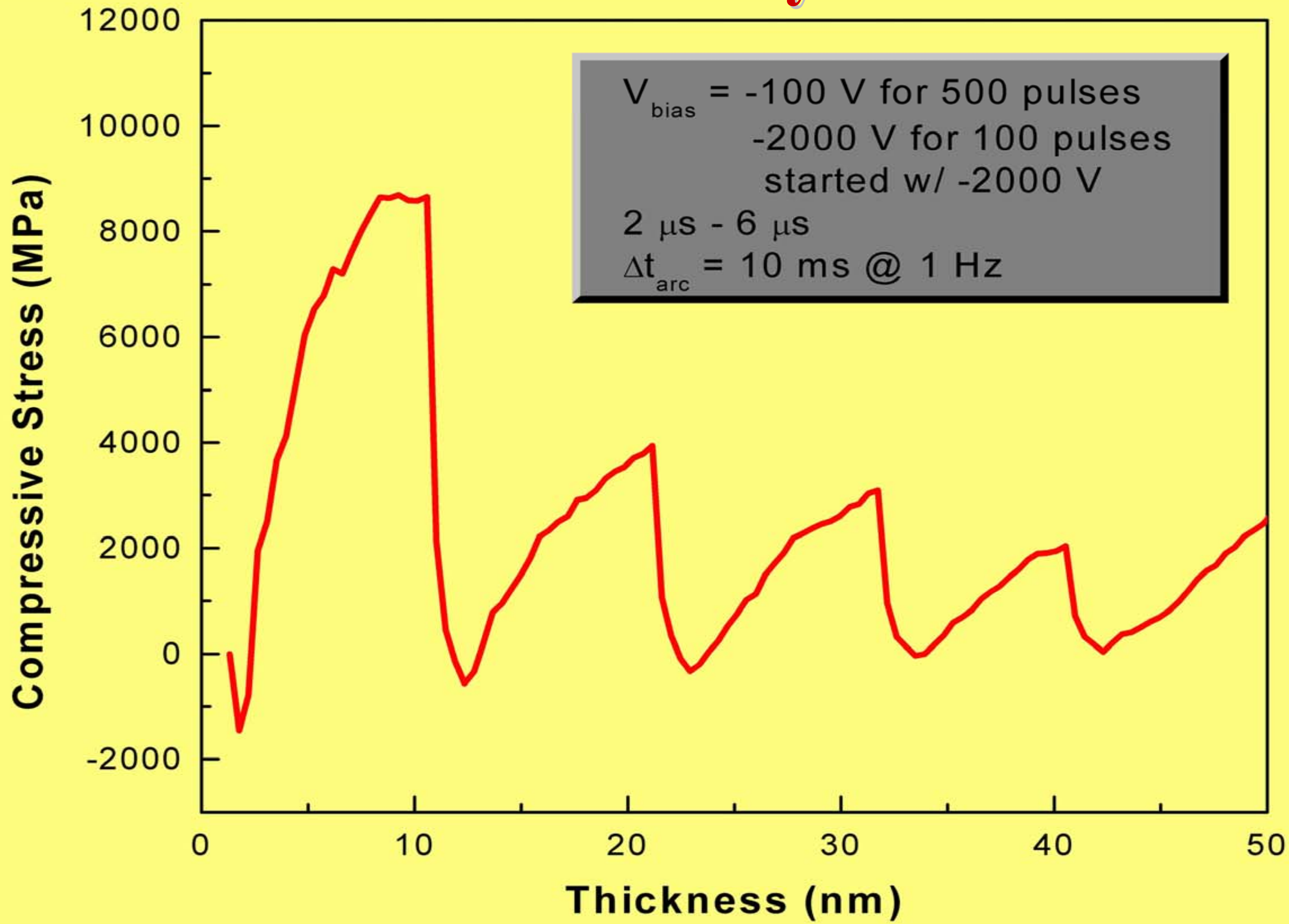
In-situ Monitoring of Stress for Stress Control by Thermal Spikes During Film Growth

Courtesy of O. Monteiro, Berkeley

Deflection of a laser beam



Stress Relaxation by Ion Bombardment



M. P. Delplancke-Ogletree and O. R. Monteiro, *Diamond Rel. Mat.* **12** (2003) 2119

Conclusions

- Cathodic arc discharge is characterized by explosive electron emission, coupled to production of cathode plasma
- Cathode plasma properties follow *Cohesive Energy Rule*
- Cathode processes are stochastic and self-organized, fractal model is most appropriate; fractal properties are found both in temporal and spatial properties
- Perhaps the oldest plasma technology, yet “emerging technology” with disadvantages and advantages
  - Macroparticles – which are addressed by filtering
  - high degree of ionization and energetic condensation to form dense films and nanostructures

In preparation:

Cathodic arc plasma deposition:
From fractal spots to energetic condensation

Springer, New York 2006